View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Michigan Technological University

Michigan Tech
Create the Future
Michigan Technological University
Digital Commons @ Michigan Tech

Dissertations, Master's Theses and Master's Reports - Open

Dissertations, Master's Theses and Master's Reports

2015

CRITERIA FOR SUSTAINABLE PRODUCT DESIGN WITH 3D PRINTING IN THE DEVELOPING WORLD

Benjamin L. Savonen
Michigan Technological University

Follow this and additional works at: https://digitalcommons.mtu.edu/etds

Part of the Industrial and Product Design Commons

Copyright 2015 Benjamin L. Savonen

Recommended Citation

Savonen, Benjamin L., "CRITERIA FOR SUSTAINABLE PRODUCT DESIGN WITH 3D PRINTING IN THE DEVELOPING WORLD", Master's report, Michigan Technological University, 2015.
https://digitalcommons.mtu.edu/etds/926

Follow this and additional works at: https://digitalcommons.mtu.edu/etds
Part of the Industrial and Product Design Commons

CRITERIA FOR SUSTAINABLE PRODUCT DESIGN WITH 3D PRINTING IN THE DEVELOPING WORLD

By

Benjamin L. Savonen

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2015

© 2015 Benjamin L. Savonen

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Environmental Engineering.

Department of Civil and Environmental Engineering

Report Advisor:	Dr. David Watkins:
Committee Member:	Dr. John Gershenson:
Committee Member:	Dr. Kurtis Paterson:
Department Chair:	Dr. David Hand

Table of Contents

List of Tables

List of Figures

Abstract

The demand for consumer goods in the developing world continues to rise as populations and economies grow. As designers, manufacturers, and consumers look for ways to address this growing demand, many are considering the possibilities of 3D printing. Due to 3D printing's flexibility and relative mobility, it is speculated that 3D printing could help to meet the growing demands of the developing world. While the merits and challenges of distributed manufacturing with 3D printing have been presented, little work has been done to determine the types of products that would be appropriate for such manufacturing.

Inspired by the author's two years of Peace Corps service in the Tanzania and the need for specialty equipment for various projects during that time, an in-depth literature search is undertaken to better understand and summarize the process and capabilities of 3D printing. Human-centered design considerations are developed to focus on the product desirability, the technical feasibility, and the financial viability of using 3D printing within Tanzania. Beginning with concerns of what Tanzanian consumers desire, many concerns later arise in regards to the feasibility of creating products that would be sufficient in strength and quality for the demands of developing world consumers. It is only after these concerns are addressed that the viability of products can be evaluated from an economic perspective.

The larger impacts of a product beyond its use are vital in determining how it will affect the social, economic, and environmental wellbeing of a developing nation such as Tanzania. Thus technology specific criteria are necessary for assessing and quantifying the broader impacts that a 3D-printed product can have within its ecosystem, and appropriate criteria are developed for this purpose.

Both sets of criteria are then demonstrated and tested while evaluating the desirability, feasibility, viability, and sustainability of printing a piece of equipment required for the author's Peace Corps service: a set of Vernier calipers. Required for science educators throughout the country, specialty equipment such as calipers initially appear to be an

ideal candidate for 3D printing, though ultimately the printing of calipers is not recommended due to current restrictions in the technology.

By examining more specific challenges and opportunities of the products 3D printing can produce, it can be better determined what place 3D printing will have in manufacturing for the developing world. Furthermore, the considerations outlined in this paper could be adapted for other manufacturing technologies and regions of the world, as human-centered design and sustainability will be critical in determining how to supply the developing world with the consumer goods it demands.

1.0 Background: Designing Products for the Bottom of the Pyramid

An increasingly popular term when discussing world economies is the phrase ‘Bottom of the Pyramid’ (BOP). Often attributed to the work of Prahalad and Hart (2002), the term is used to refer to the globe’s four billion poorest people and the possibilities that exist for companies to be able to enter these markets and make financial gains while improving livelihoods. These four billion people are mostly people from Africa, Asia, and Latin America who individually have an annual income of less than 3,000 USD a year but a collective purchasing power of five trillion USD (Hammond, 2007). The BOP movement signifies a shift in thinking from regarding the global poor as not pitiable and helpless, but a group of consumers able to participate in the global economy (Prahalad and Hart, 2002). Prahalad and Hart’s work suggests that it may be profitable for companies to diversify and redesign their products to be more culturally and economically appropriate for these BOP markets in order to better promote the welfare of both companies and consumers (Sesan et al., 2013). While it is not universally agreed that marketing to the BOP is positive for development (Karnani, 2007), many agree that designing and producing for the BOP is in line with promoting economic growth for developing countries. As products and services are beginning to be catered to the needs of this segment, it becomes crucial that sustainability be integrated into the process at the design phase (Castillo et al., 2011).

Sub-Saharan African economies will be among some of the world’s fastest growing this decade (Hatch et al., 2011). The continent’s population is rapidly growing, as is its expenditures on consumer goods, which is expected to grow from 600 billion USD to over one trillion USD by 2020 (Hatch et al., 2011). Consumers who fit under the category of BOP comprise nearly 71% of the purchasing power and 95% of the population of Sub-Saharan Africa (Hammond, 2007). As the population continues to rise, along with its purchasing power, the BOP will have a continually higher demand for consumer products.

1.1 The Developing World and 3D Printing

There has been much growth and excitement about the possibilities additive manufacturing (AM) techniques can bring to the world economy. Hailed by some as the ‘next industrial revolution’, AM (or 3D printing as it is more often referred to) is expected by many to change the way products and goods are manufactured by reducing the need for intensive supply chains, large inventories, high labor costs, and global emissions (Berman, 2012; Campbell et al., 2011).

3D printing is not one technique, but a set of manufacturing techniques that utilize three dimensional Computer Aided Design (CAD) drawings to fabricate 3D objects. These techniques slice the object into layers and build the object by depositing one layer of material on top of another until the entire model is constructed. Unlike traditional subtractive manufacturing techniques which rely on removing material from a raw material source in order to achieve a desired geometry, 3D printing processes have little waste material left behind and do not require a variety of tools and molds to complete manufacturing (Petrovic et al., 2011). Most printers are able to manufacture a part with no inputs beyond the raw material, electrical energy, and data. Different printing processes have been developed for a variety of materials. Some examples taken from Petrovic et al. are summarized and can be seen in the Table 1 below.

Table 1. Additive manufacturing methods and materials adapted from Petrovic et al. (2011)

AM Process	**Materials**	**Description**
Stereolithography (SLA)	Plastics/polymers	Uses lasers to achieve photopolymerization, binding resins together.
Selective Laser Sintering (SLS)	Polyamides with glass or aluminum	Uses lasers to fuse polymers together
Digital Light Processing (DLP)	Photosynthetic resins	Uses ultraviolet light to solidify photosensitive resins
Fused Deposition Modeling (FDM)	Plastics/polymers	Deposits layers of melted thermoplastic on top of one another
Selective Laser Melting (SLM)	Various metals	Uses lasers to fuse metal particles together
Electron Beam Melting (EBM)	Various metals	Uses electron beams to fuse metal particles together

These manufacturing methods are already used widely throughout the industrialized world for manufacturing of products and components that cannot be as easily or economically manufactured through other methods. It is estimated that the AM industry grows by 25-30% per year, with the consumer products and electronics, biomedical, and transportation industries using AM most prominently (Yeh, 2014). However, the use of 3D-printed technologies is not extensive in the developing world, though many speculate that it has tremendous potential for impact. Most of its perceived potential revolves around the ability of the technology to decentralize manufacturing. The ability to create manufacturing jobs, lower the costs of certain products, and the ability to quickly make culturally appropriate design changes make 3D printing an appealing technology for developing world economies (Campbell et al, 2011; Ishengoma and Mtaho, 2014; Gebler et al., 2014).

Manufacturing with minimal infrastructure, often something severely lacking in the developing world, has the ability to stimulate local economies and decrease dependency on remote or foreign supply chains that often do very little to benefit the people within a region (Pirjan and Petrosanu, 2013). It has been demonstrated that the most effective means of economic growth within a region are operations on a small scale that encourage small business development (Polak, 2008), and proponents of 3D printing believe the technology could be an important way of enabling such development (Ishengoma and Mtaho, 2014; Pearce et al., 2010; Birtchnell and Hoyle, 2014).

The potential that 3D printing technologies has for use in humanitarian relief applications throughout the developing world has also been considered, though less thoroughly explored. Some have suggested that 3D printing would be able to simplify and reduce costs and logistical challenges associated with relief efforts, as only raw material and an energy source would need to be present at the site of relief activities (Tatham, et al, 2014). The application of 3D printing could allow necessary hardware and tools to be constructed quickly, on site, and as they are needed (Tatham, et al, 2014).

Another benefit of 3D printing is the ability to freely share designs for products across the world through the usage of the internet. Standard Tesselation Language (STL) files can be created anywhere in the world and shared to create objects that can be manufactured by a 3D printer. This flexibility effectively allows product design and manufacturing to be separate processes (Berman, 2012).

Physical products could follow the path that media has undergone with digital music and video files and electronic books (Campbell et al, 2011; Berman, 2012), transforming, as Gershenfield (2012) says, “data into things and things into data”. Many proponents of 3D printing technologies advocate taking this freedom a step further, implementing 3D printing to promote open source appropriate technology. This includes a vision of free sharing of product designs, collaborative designing, self-replicating printers, and manufacturing availability to more communities including those in the developing world (Pearce et al., 2010; Birtchnell and Hoyle, 2014).

While the potential for 3D printing to be utilized in the developing world certainly exists, it remains to be seen if 3D printing can be successfully applied as many hope. Until now, the application of 3D printing in the developing world has been limited, mostly confined to universities or small scale innovation or “incubator” type settings (Ishengoma and Mtaho, 2014). The implementation mostly likely lags due to the several barriers the technology faces. Most of these barriers are technological, including, but not limited to: machine costs and maintenance, too few material choices, material costs, low part quality, and inconsistent energy availability (Berman, 2012; Tatham et al., 2014; Pirjan and Petrosanu, 2013). Those in the developing world acknowledge that the technical understanding currently required for the operation of software and printers will also remain one of the largest challenges for the technology to overcome (Ishengoma and Mtaho, 2014). It is because of these obstacles, among others, that 3D printing has yet to see full scale adoption in both the developed and developing world, and it may be several years to a decade until the technology is ready for mainstream adoption (Garter, 2014).

Most sources [e.g., Pearce et al. (2010); Birtchnell and Hoyle (2014)] are optimistic that 3D printing has a place in producing goods for sustainable development; however, it is not yet known what that place is. As the Sub-Saharan African consumers continue to grow in numbers and purchasing power (Hattingh et al., 2012), the demand for consumer goods will increase, and it is possible that 3D printing might help to meet those demands sustainably.

The purpose of this paper, however, is not to assess the technology of 3D printing as a whole, but rather to begin to consider what types of products would be most suitable for manufacture with this technology, specifically within the developing world. This will be done by first describing the experiences of the author in Tanzania and how 3D-printed products could potentially fit into Tanzanian economies. Next, two sets of criteria will be developed for evaluating a product's suitability for 3D printing in similar markets. Finally, a case study will be examined to demonstrate the proposed criteria.

These criteria, illustrated through the case study, may be applied to any product that would potentially be printed for use in the developing world. Designers and manufacturers can use this information to make design decisions for products and to better understand the product and consumer ecosystem associated with a 3D-printed product in the developing world, before moving forward with production. Additionally, local entrepreneurs or those working in small business development could use these criteria to evaluate the viability and product offerings of a potential enterprise before investing capital. These considerations can be used to assess the points within developing world markets in which 3D-printed products could first be implemented as well as contribute to the ongoing discussion of the application and further development of this technology in the developing world.

2.0 Project Motivation

The desire to look into the potential application of 3D printing technologies for BOP product design was inspired by the author's two years of Peace Corps Service in the United Republic of Tanzania.

2.1 Tanzania and the Need for Development

Tanzania is located in Sub-Saharan East Africa bordered to the north by Kenya and Uganda; to the west by Rwanda, Burundi, and the Democratic Republic of Congo; to the south by Malawi, Zambia, and Mozambique; and to the east by the Indian Ocean. As seen in Figure 1 below, Tanzania is comprised of two states: Mainland Tanzania (formerly Tanganyika) and the semiautonomous island of Zanzibar.

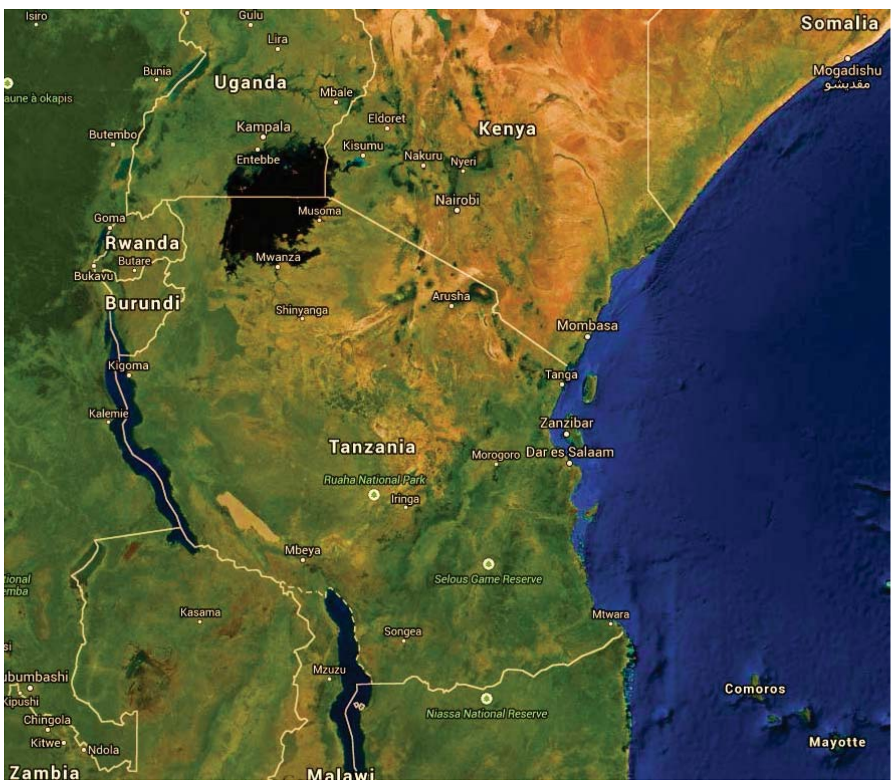


Figure 1. Map of Tanzania (Google Maps)

As of June 2014, Tanzania was home to over 49 million people, with a median age of 17.4 years, making Tanzania a young country (CIA, 2014). Poverty and the need for development are real concerns, as Tanzania ranks 159 out of the 187 countries on the Human Development Index (United Nations Development Program, 2013). As of 2012, 28% of its population was under Tanzania's internally defined poverty line, and the majority of this population dwelled in rural areas (National Bureau of Statistics, 2013). Census data from 2012 indicated that household farming was 73.6% of all Tanzanian's primary occupation with the next largest segment (12.3%) of the population being self-employed, small business owners (National Bureau of Statistics, 2013). With a GDP Purchasing Power Parity of 1,700 USD per capita (CIA, 2014), Tanzania's consumers fall right into the BOP as defined by Prahalad and Hart (2002). Tanzania's needs and abilities to purchase consumer goods have been demonstrated, as consumer goods, primarily from India and China, are currently its primary import (CIA, 2014).

2.2 Applicability of 3D printing Technology to Peace Corps Service

The author's Peace Corps service took place in the northern part of the Iringa region, part of Tanzania's southern highlands and bordering the central desert region of Dodoma. While the bulk of the Iringa region is characterized by greenery and hills, the author's site resembled the central deserts and was considered by its inhabitants to be a semi-arid climate. The region's primary industry, however, is agriculture, with maize and sunflower being the primary cash crops. An example of the typical scenery of Ismani can be seen in Figures 2 and 3 below.

Figure 3. Ismani homestead (photo by author)

Figure 2. Iringa-Dodoma road (photo by author)

The municipality of Ismani is located in the *Iringa Vijijini* (Iringa Rural) district. The village is directly north of the regional capital, Iringa, along the Iringa-Dodoma highway. It contains roughly 20,000 people and 15 villages. The largest village, Lwang'a, is more commonly known by the name of the region, Ismani, and is the administrative village of the municipality. The entire area was historically known for its fertility in growing grains. Though agriculture remains its primary industry, Ismani has become increasingly arid, something which most attribute to over-farming and deforestation (Kijazi et al., 2013).

Iringa town is the cultural and economic hub of the region, being one of the largest towns in the southern highlands. Iringa town is the headquarters of many Non-Governmental Organizations (NGO) and Tanzanian government offices. Ismani is 45 kilometers north of Iringa town and can be accessed by multiple buses throughout the day. A map of Ismani in relation to Iringa town can be seen in Figure 4 below.

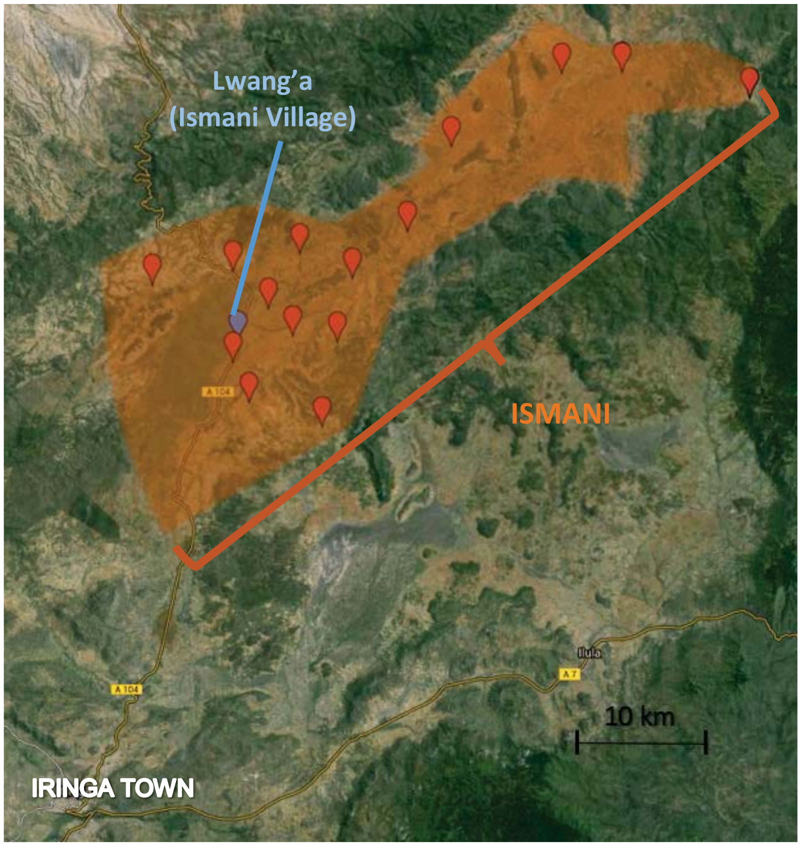


Figure 4. Map of villages of Ismani in relation to Iringa town, with Lwang'a marked in blue (made by author with Google Maps)

The Ismani village has the area's only hospital and one of its three secondary schools. The author's Peace Corps assignment was to teach physics and chemistry at Ismani Secondary school. It is a school of approximately 700 students between the ages of 14 and 20. There were at any point in time 12-20 teachers at the school over the course of the author's two years of service (2012-2014). Science and mathematics teachers were few, and at times the author was one of only three teachers teaching physics, chemistry, biology, and mathematics. Teacher turnover is high in Tanzania and exceptionally so for the rural school of Ismani Secondary.

In addition to teaching, the author was involved in many secondary activities within the community, including school laboratory development, solar food driers, youth empowerment clubs, the cataloging of the local language, and the construction of an auxiliary water supply line for the village hospital and clinic.

All of these projects accompanying the author's Peace Corps service required the procurement of specific tools and supplies that could not be acquired from within the village. Laboratory equipment, pump hardware, bicycle parts, and other parts not acquirable at the small *maduka* (general stores) of the village typically required a day of travel time and fares that many people of Ismani find prohibitively expensive.

As the people of Ismani struggle every year to make a living with agriculture, new sources of economic growth become necessary. Additionally, with the only hospital, one of the few secondary schools, and a large grain mill all centered in Ismani, there are often needs for equipment and parts. With Ismani's location in its village cluster, its recent connection to the electrical grid, and highway access to Iringa town, Ismani has the potential for a distributed manufacturing operation through 3D printing.

Nowhere in Tanzania has 3D printing been utilized for the distributed manufacturing of consumer goods. The only prominent instance of 3D printing technology being used in the country is a collaboration of the Tanzanian and Finnish government known as TANZICT, which seeks to promote the development of Tanzania's technology sector (Edwards, 2015). TANZICT has developed labs and programs to train young Tanzanians to construct and use 3D printers made from e-waste (Edwards, 2015). This endeavor is still far from a direct application in manufacturing, however.

3.0 Developing Criteria for Evaluating 3D-printed Products Using Human Centered Design

There are many different parameters that have been developed to assess engineering projects and products. The first three criteria to be used in this report are those introduced by the design firm IDEO, in their works on human-centered design. IDEO suggests for a product to be considered successful the product must be simultaneously desirable, viable, and feasible (2009).

The first criterion, desirability, is concerned with how a product or service is able to satisfy the needs of the user (Castillo et al., 2011). It is concerned with the "human factors" of a design (Weiss, 2002) and asks, "What do people want?" when evaluating a potential solution (IDEO, 2009). Criteria related to desirability look to ensure that engineering solutions will be something consumers are willing to use and pay for.

Feasibility looks for effective ways to use technological possibilities to meet the needs of the user (Castillo et al., 2011). It analyzes the "technical factors" associated with engineering solutions (Weiss, 2002) and investigates, "What is technically and organizationally feasible?" (IDEO, 2009). Criteria related to feasibility are concerned with the successful application of technology to an engineering solution.

A viable solution needs to be accompanied by a strong model for economic success (Castillo et al., 2011). Viability criteria revolve around the question of, "What can be financially viable?" (IDEO, 2009) and are largely centered on the "business factors" (Weiss, 2002).

This model, developed by IDEO, has been embraced and used by many others to evaluate potential products and projects. While it is stressed that all three criteria need to be fulfilled, human-centered design also stresses the importance of beginning any project by investigating concerns relating to desirability first, and then moving on to feasibility and viability concerns (IDEO, 2009). This is because a technology or business can most easily be limited by user acceptance, and thus should not be pursued until desirability is resolved (Brown, 2009).

The goal of this chapter is to determine the desirability, feasibility, and viability of a product to be designed for the developing world and manufactured through 3D printing. These questions would be used by current and future designers when considering a product for manufacturing through 3D printing or an entrepreneur considering printing products that could become a part of their business's offerings. By using this human-centered design criteria before production, either party would be able to evaluate the ability of a product to successfully find a place within its market. Being able to answer these questions within the context of the developing world requires the addressing of many more specific questions tailored to a specific market and culture in which a product would be offered.

3.1 Desirability

Desirability is one of the more difficult elements in the design process to evaluate, but it is also the most important (IDEO, 2009). It is the ability of a design solution to "motivate consumer behavior" (Weiss, 2002) or a solution that "makes sense to people and for people" (Brown, 2009). Desirability can vary dramatically by individual and culture and cannot always be easily quantified. To evaluate whether or not a 3D-printed product could be suitable for a market, it must be determined if a space for the product exists in the market and how the product is potentially able to benefit consumers.

3.1.1 Defining Desirability

Though questions regarding desirability are questions that should be addressed by many fields, including sociology, anthropology, and psychology, it is important for engineers to take into account the motivations behind the purchasing of a product when considering its desirability. It is the desirability and cultural appropriateness of a product that ultimately determines its success (Jacobs, 2007). Regardless of its importance, frameworks for effectively quantifying and evaluating a product's desirability have yet to be sufficiently developed. Such frameworks would need to be developed to be adaptable to specific markets and cultures.

The satisfaction acquired from a product increases the importance a user attributes to it, and this importance determines the product's value and place within the economy and potentially extends the product's lifespan (Diegel et al., 2013; Govers and Mugge, 2004).

3.1.2 Considerations for Evaluating Desirability

While there are a many ways to determine what is considered desirable in a culture, this section looks to evaluate desirability based on examining existing market spaces and by determining how a product is able to benefit a user through a series of questions.

Desirability Question 1: Has the desirability of this product already been demonstrated through a comparable product in the market?

When considering the potential of 3D printing a part in the developing world, it does not mean that an entirely new product is being created. If a product to be printed is simply a 3D-printed version of a product already existing within the marketspace, it can be assumed that some desirability for such a product already exists. In this case, deciding to print an object with additive manufacturing is merely supplying an established product through a different means of production. The demand of a product could be quantified by determining the number of similar and competitive product offerings available within the marketspace and the quantities being sold. Some relatively simple market analysis can quantify these demands present within a marketspace.

The total demand for a 3D printed product does not necessarily need to be high, however, for a product to be desirable or viable. It is only necessary to see that some demand does exist in order for a product to be considered for printing.

A 3D-printed version of a product should be evaluated to determine if it could have any additional benefits over a traditionally manufactured comparable product. With the general geometric flexibility that 3D printing provides, designers can more freely design value and desirability into their designs with less concern for manufacturing constraints (Campbell et al., 2013; Pirjan and Petrosanu, 2013; Diegel et al., 2010).

Desirability Question 2: Will the perceived benefits of an existing product be increased by manufacturing it through 3D printing?

Convincing consumers to purchase a product or brand that they are unfamiliar with requires additional motivation on the part of a consumer. Porter (1980) states that a product can compete effectively in its market by either decreasing the product's cost, tailoring a product to the needs of specific customer groups, or differentiating the product's perceived quality from other brands.

When considering the BOP, it is important not to aggregate all of its 4 billion consumers together. Still, some general trends do emerge, and cost reduction is one obvious way to make a product more appealing to resource constrained BOP consumers of Sub-Saharan Africa. However, cheaper products can often be associated with inferior quality, and, contrary to what is perhaps believed, consumers in Sub-Saharan Africa still generally show demand for quality products (Hattingh et al., 2012). Consumer decisions are not made based only on price and utility, and thus dropping the price alone may not make a product more desirable. Rather, in order to be competitive, the perceived value of the product should be maintained or improved while cost is decreased.

Brand loyalty is a notable feature in consumer behavior in Sub-Saharan Africa due to a low-risk buying mentality (Boston, 2009; Hattingh et al., 2012). It is suspected that this is directly related to limited incomes, i.e., consumers look to maximize the dollars that they spend (Boston, 2009). On more than one occasion the author would hear people remark how a certain brand of products sold in Tanzania were *kichina* (slang for a 'knock-off' lower quality product imported from China). This general consciousness about brand quality could also be due to low access to information about products. If consumers find a brand that is able to fulfill their needs, they choose to only purchase that which has proven trustworthy and is therefore a lower risk for their constrained budgets (Boston, 2009; Hattingh et al., 2012). Brand recognition will be harder to establish with 3D printed products, because the quality of products with the same design can still vary widely based on its specific build parameters. To be able to determine if a product will be desired or considered to be of higher quality than existing products in a marketspace requires a thorough understanding of the consumer’s culture (IDEO, 2009; Human Factors International, 2011).

It is difficult, but not impossible, to quantify or accurately describe what consumers consider desirable. A new product should be evaluated primarily in terms of the benefits that the product brings the user (Lai, 1995). Such benefits are not only the directly observed or “extrinsic experiences” that a product can provide by performing its utilitarian function for the user, but also the “intrinsic experiences” that the product is able to provide by helping the user experience specific emotional benefits (Campbell et al., 2013). Lai (1995) describes the eight different types of overlapping benefits that products can potentially bring users, only one of which can be directly tied to the product’s ability to perform its primary function. These benefits are described in Table 2.

Table 2. Product Benefit Types adapted from Lai (1995).

Benefit Type	**Description**
Functional	The ability to derive utilitarian benefit from the product
Social	The ability to alter the user’s perceived social status
Affective	The ability of a product to elicit specific sentimental emotions in the user
Epistemic	The ability of a product to provide novelty, new knowledge or experiences
Aesthetic	The ability of a product to improve one’s personal expression
Hedonic	The ability of a product to directly provide pleasure to the user
Situational	The ability of a product to alter the situation surrounding its use
Holistic	The product’s perceived ability to promote the user’s overall wellbeing

All eight benefits are overlapping with one another, and it is readily evident that all of the benefits are heavily influenced by personal and cultural values (Lai, 1995). Assessing any of the benefits requires significant investment in learning about a culture, as market research for specific cultural settings within the BOP is generally limited. One can try to make overarching assessments about the culture of a consumer population, but even then, such generalizations will vary significantly from subculture to subculture. While Lai's criteria can be applied to most cultures, knowing how to practically apply these criteria can prove to be challenging.

If a newly introduced product is to be successfully marketed to a population, one should be able to answer if and how the product will benefit the user in any of the categories of Table 2 and how these benefits compare to those of a product's nearest competitors within a market space. It is proposed that these benefits be evaluated on the scale given in Table 3.

Table 3. Scale for ranking a product's ability to provide benefits

Benefit Level (B)	**Description**
0	The product provides no foreseeable benefit in this regard
1	The product may possibly provide this benefit as an unintended consequence of design
2	This product will probably provide this benefit as a result of design, though as the result of secondary design considerations
3	This product will almost certainly provide this benefit

By utilizing this scale, the ability of a product to supply each of all eight of Lai's benefit types can be quantified, summed as a measure of total benefit,, and compared to a product's nearest competitor within a marketspace by using Equation 1.

$$\text{benefit ratio} = \frac{\Sigma B_{3D\ printed}}{\Sigma B_{competitor}} \qquad \text{Equation 1}$$

where $\Sigma B_{3D\ printed}$= the total of the benefit levels seen for all eight benefit types for a 3D printed product (numerical value, 0-24)

$\Sigma B_{competitor}$= the total of the benefit levels seen for all eight benefit types for a 3D printed product's closest competitor (numerical value, 0-24)

Both totals can be calculated using Equation 2.

$$\Sigma B = B_{functional} + B_{social} + B_{affective} + B_{epistemic} + B_{aesthetic} + B_{hedonic} + B_{situational} + B_{holistic} \qquad \text{Equation 2}$$

where $B_{functional}$ = the ability of a product to supply functional benefits (numerical value, 0-3)

B_{social} = the ability of a product to supply social benefits (numerical value, 0-3)

$B_{affective}$ = the ability of a product to supply affective benefits (numerical value, 0-3)

$B_{epistemic}$ = the ability of a product to supply epistemic benefits (numerical value, 0-3)

$B_{aesthetic}$ = the ability of a product to supply aesthetic benefits (numerical value, 0-3)

$B_{hedonic}$ = the ability of a product to supply hedonic benefits (numerical value, 0-3)

$B_{situational}$ = the ability of a product to supply situational benefits (numerical value, 0-3)

$B_{holistic}$ = the ability of a product to supply holistic benefits (numerical value, 0-3)

The greater the value of total benefit ratio, the more perceived benefits a user would expect to be able to receive from its use compared to a competing product. If the benefit ratio is significantly less than 1, a 3D printed product should not be considered more desirable than its competitors. For instance, when designing for Sub-Saharan African consumers, social and aesthetic benefits are especially important factors in evaluating a product's desirability (Hattingh et al., 2012). Social benefits are especially important in many developing world cultures where interpersonal relationships are held in especially high importance (Ger et al., 1993). Both the author's personal observations and studies (Boston, 2009) show that the status conveyed by one's purchases is important to many Sub-Saharan African consumers. For example, younger consumers are particularly are drawn to products that reflect western styles as they are continually exposed to more western culture through media (Hattingh et al., 2012; Donaldson 2006). Such western products can promote social standing by being associated with progress, just as other foreign products are often perceived to be of higher quality when compared to products produced locally (Batra et al., 2014). Because of the variability in the level of importance a culture places on a benefit, future work should be conducted to incorporate a relative weighting of the benefits in Equation 2. Based on a specific culture's values, different benefits may be viewed the same way.

Understanding the relative importance of these benefits can require significant amounts of time and research, and much material has been written from a variety of perspectives on how to best integrate one's self into a culture for the purpose of understanding cultural values for improved product design [e.g. IDEO, (2009) or Human Factors International, (2011)]. Most sources suggest a participatory design approach when designing products for use in a culture or subculture different then the designer's own (IDEO, 2009; Human Factors International, 2011). By enlisting the assistance of people indigenous to a culture to help in the design process, designers are able to more naturally incorporate desirability into a product. One must be careful in the methodology one uses, however; as the author and others have noted, it is not uncommon for those participating in design processes to be biased in their advising (Human Factors International, 2011; White et al., 2008). Thus, allowing said participants to take co-leadership design roles is often necessary to learn what should be included when defining criteria for desirability assessment (Sanders and Strappers, 2008). In other words, effective design cannot be done from outside of the cultural being designed for (Donaldson, 2009). This means that a perceived benefit of 3D printing could actually be a pitfall, as the ability to remotely prepare designs and CAD files could lead to increased products being made without proper knowledge of cultural context (Melles et al., 2011).

A more practical benefit of 3D printing in the design process is that it allows much faster development cycles than would be possible with other manufacturing methods (Beyer, 2014). Thus, product experimentation can occur without tying up massive amounts of capital, providing a shorter feedback loop to the designers. With 3D printing, a single product can be manufactured without an investment in tooling (Gebler et al., 2014). The most that can be lost is the material and energy needed to produce a single part and the time to produce a CAD drawing. However, even this rapid prototyping ability may be limited in its usefulness, as most innovations coming out of the developing world are only incremental improvements of existing solutions, or imitations of western products, and are rarely novel designs (United Nations Environment Programme, 2009).

This observed lack of novelty falls in line with the observations of the author and the findings of a study performed by Donaldson (2006) in Kenya. Donaldson (2009) also suggests that this observed lack of innovation is due to a culture of low material access where tinkering and prototyping is considered a waste of resources. The author of this paper concedes this may be one among many factors influencing the lack of innovation observed in Tanzania, which should also include lack of education in design/problem solving thinking (United Nations Environment Programme, 2009) and a culture that generally does not value individuality. Thus, even with the creative manufacturing potential of 3D printing, the amount of novel designs coming out of East Africa would probably still be few. The option of locally controlling manufacturing may not necessarily lead to an immediate increase of innovations and new designs as many proponents, [e.g. Pearce et al., (2010) or Birtchnell and Hoyle, (2014)] of 3D printing for appropriate technology may hope.

3.2 Feasibility

Feasibility regards the ability of the product to be manufactured, serve its intended functions, and supply its intended benefits. Weiss (2002) refers to feasibility as determining how “technologies can be harnessed to make a nascent product or service concept come to life in a way that is meaningful for use”. Tim Brown (2009), CEO of IDEO says feasibility is finding, “what is functionally possible in the foreseeable future”.

3.2.1 Defining Feasibility

There are a number of technological limitations that should be considered when the feasibility of 3D printing is discussed. It should be noted that most of the concerns and constraints discussed in this section reflect the current state of the technology and may become less significant in years to come.

There are many different methods of 3D printing, however, most discussions concerning 3D printing in the developing world revolve around fused deposition modeling (FDM), and that is what will primarily be considered in this paper. The increased prevalence of FDM printers over other technologies is due to FDM printer’s transportability, low overhead investment, low technical expertise needed to operate and maintain, and low maintenance costs. (Tatham et al., 2014; Durgun and Ertan, 2014).

FDM operates by taking a CAD model and slicing the model into thin layers stacked vertically. These thin layers are then built by a mobile extruding printer head depositing lines of hot plastic filament in the shape of the completed part. Examples of a low-cost 3D printer and parts it creates and can be seen in Figures 5 and Figure 6, respectively.

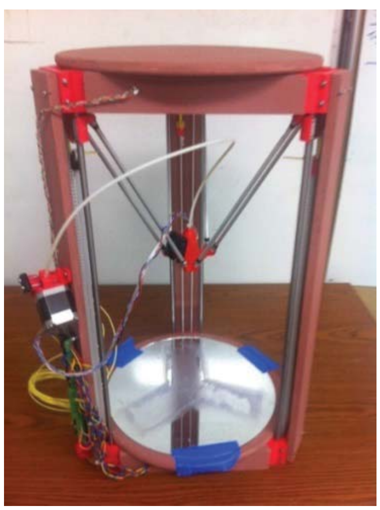


Figure 6. RepRap Printer (photo by author)

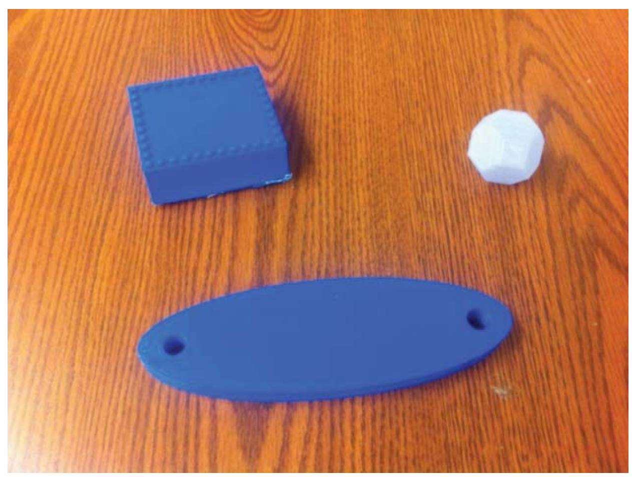


Figure 5. Parts made with FDM (photo by author)

3.2.2 Considerations for Evaluating Feasibility

As with parts made with any manufacturing method, there are requirements, constraints, and capabilities specific to 3D-printed parts. Different functions, features, and constraints may make a product a better or worse candidate for being 3D-printed. Geometric complexity, customization, material properties, mechanical properties, part sizes, and tolerances all affect whether or not a part is appropriate to print.

Feasibility Question 1: Does the part have an exceptionally complex geometry that could not be achieved with other manufacturing methods?

One of the distinct advantages of 3D printing is its ability to manufacture products of complex or unique geometries with "no additional" cost (Nyman and Sarlin, 2014). Thus if a part has a specific or complex geometry that requires extensive tooling to manufacture with traditional methods, it may be advantageous to use 3D printing to produce it. While the notion of "free complexity" is not completely true and will be addressed in the viability section of this paper, it is true that additive manufacturing techniques do have a distinct advantage over traditional manufacturing techniques in that complex geometries can be achieved using only one machine. No new tooling is generally necessary to begin producing a new part or design (Gebler et al., 2014). All that is required to print is a file with a new CAD model. The building of a part by layers removes many restrictions to what can be made; however, the technology is not limitless. Many parts cannot be made without constructing support structures alongside the part. If the part's geometry is overly dependent on these support structures, it may be possible that a part could be printed but not survive the support's removal, subsequent cleaning, and post processing (Stava et al., 2012).

Attempts have been made to quantify a 3D-printed part's complexity (Conner et al., 2014; Valentan et al., 2008; Valentan et al., 2012). Generally, most methods rely on relating a part's volume to its surface area, or its volume to the volume of a box based on its maximum dimensions (Valentan et al., 2008). From the literature available there does not appear to be a consensus on how to quantify a 3D-printed part's complexity, and some degree of expert manufacturing opinion is often incorporated (Valentan et al., 2008; Valentan et al., 2012).

Feasibility Question 2: What level of customizability is required for this part?

It is often regarded that one of 3D printing's greatest strengths is its ability to introduce customization to a product without any additional cost (Conner et al., 2014). Whether it is customization for product desirability or customization needed for functionality (as in use with biomedical applications), customization can add much value to a product. Any parts that have previously been designed as "one-size-fits-all" could be redesigned to allow for customization, and therefore more desirability and economic value (Campbell et al., 2013).

The extent to which customization is useful will vary significantly by part, and it is useful to establish criteria for determining what a product stands to gain. Conner et al. (2014) created a scale for measuring a product's need for customization, shown in Table 4. According to this scale, products with ratings of 0 or 1 may not benefit drastically from 3D printing, those products with 2 or greater should strongly be considered.

Table 4. Scale for rating a product's need for customization from Conner et al. (2014).

Customization Rating	**Description**
0	No customization, all products are the same
1	Several predefined versions of a product (i.e. different sizes or colors)
2	Product has one feature that is fully customizable and definable by the user
3	Product has several feature that is fully customizable and definable by the user
4	Product is truly unique

The ability to customize is entirely dependent on the printer operator's ability to manipulate CAD drawings. Lack of technical skill may make simple customizations difficult, and advances in software will be needed before customization is possible for more users.

Feasibility Question 3: What is the build envelope of the product?

Most open source printers currently available are relatively small and have limited build envelopes, or volumes in which they are able to build (Conner et al., 2014). Typically the build envelope of the product refers to the product's maximum length, width and height. If this box is not able to fit in the build envelope of the printer being used, the part either cannot be made on that printer or must be redesigned to be modular in order to be printed in pieces and assembled after construction. A comparison compiled by Pirijan and Petrosanu (2013) of some achievable build envelopes of low cost 3D printers can be seen in Table 5.

Table 5. Build envelopes of low-cost 3D printers

Printer	**Build envelope (mm - mm - mm)**
Cupcake CNC	120-120-115
Makerbot Replicator	225-145-150
MakerGear Mosaic M1	127-127-127
Ultimaker	210-210-220
WhiteAntCNC	160-190-125
MendelMax	250-250-200
PrintrBot	150-150-150
RepRap Wallace	200-200-200
RepRap Huxley	140-140-110
PrusaMendel	200-200-110
AO-100	200-190-1000

Additionally, as 3D printed parts are printed layer by layer, larger objects, even if possible to fit into the build envelope, may become far more costly than other manufacturing methods in regards to time and energy used (Lu et al., 2014).

Feasibility Question 4: Does this part benefit from having a low density?

If the part has low required densities or specific internal geometries, 3D printing may be the best choice in regards to manufacturing of a product (Conner et al., 2014). 3D-printed parts are able to achieve low densities due to the advantage of being able to control the interior geometry during construction (Lu et al., 2014). It is this advantage that gives the manufacturing technique a distinct advantage over rival manufacturing methods, and it is probably why 3D printing is often used in the aircraft industry. Removing material from the interior of a part can also reduce time and material costs (Lu et al., 2014).

The materials used as filament for FDM 3D printing are mostly plastics and largely have similar physical, chemical, and mechanical properties including density. Some of the more common materials are Acrylonitrile Butadiene Styrene (ABS), Polylactide (PLA), Polyvinyl Alcohol (PVA), High Impact Polystyrene (HIPS), Nylon, Wood particle-infused plastic, Polyethylene Terephthalate (PET), PETT, Polycarbonate (PC), Thermoplastic Elastomers (TPE), and many others (3D Printing, 2015). Though material choices are greater than the plastics listed, they are still relatively limited. The two most commonly used plastics for FDM are ABS and PLA (Chennakesava and Nayaran, 2014). The other plastic to be considered throughout this report will be HDPE, as it has the potential for developing world use due to the existence of mobile recycling systems for producing filament such as Recyclebot (Baechler et al., 2013).

Feasibility Question 5: What are the maximum temperatures this product will be exposed to?

Any products printed with FDM must be designed with the material properties of plastics in mind. A comparison by Hamod (2015) of some of the thermal properties of these plastics can be seen in Table 6.

Table 6. Thermal properties of common filament types adapted from Hamod (2015).

Property	**ABS**	**PLA**	**HDPE**
Glass Transition Temperature	100 °C	50-60 °C	80-110 °C
Extrusion Temperature	210-230 °C	160-220 °C	130-190 °C
Melting Temperature	200-230 °C	120-190°C	190 °C

All of the plastics used have relatively low melting points and are not able to be used for products that are subjected to high temperatures.

Due to the nature of FDM techniques, printed objects have anisotropic mechanical properties that differ greatly from the mechanical properties of similar ABS parts manufactured through most other methods (Ahn et al., 2002; Tymrak et al., 2014). Some examples of these differences can be seen in Table 7 below.

Table 7. Examples of mechanical properties differences between extruded ABS to 3D-printed ABS parts as found in literature

Mechanical Property	**ABS (Extruded)**	**Printed ABS Part (Maximum value from literature)**	**Printed ABS Part (Minimum value from literature)**
Tensile Strength	52 MPa (INEOS, 2009.)	35 MPa (Raut et al., 2014)	4.0 MPa (Ahn et al., 2002)
Flexural Strength	75 MPa (INEOS, 2009.)	65 MPa (Durgun and Ertan, 2014)	19 MPa (Sood et al., 2010)
Elastic Modulus	2.3 GPa (INEOS, 2009.)	1.9 GPa (Tymrak, et al, 2014)	1.7 GPa (Tymrak et al, 2014)

Build orientation, raster angle, layer height, deposition temperature, infill density and deposition speed can all have significant effects on the mechanical properties of a part. Build orientation refers to the positioning of the part to be manufactured in relation to the x, y, and z axis of the printer (Chennakesava and Narayan, 2014) and is demonstrated in Figure 7.

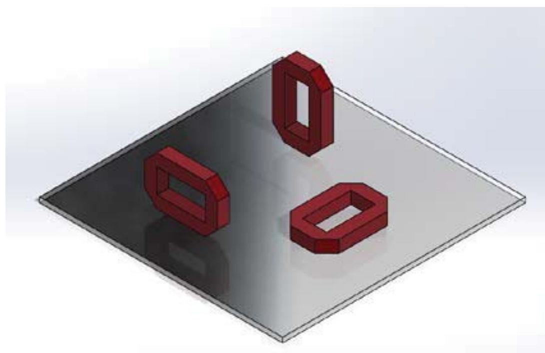


Figure 7. Examples of possible build orientations of a single part
(rendered by author using Solidworks)

The raster angle is related to the angle at which filament is laid in reference to the X and Y axis of printer bed (Chennakesava and Narayan, 2014). Though the raster angle actually refers to the angle at which lines of filament are deposited, one can control the raster angle by adjusting the positioning of the part on the printer bed as seen in Figure 8.

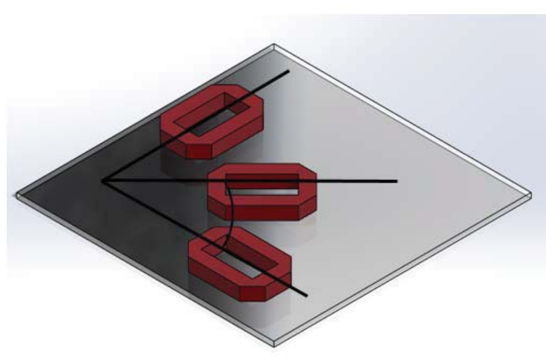


Figure 8. Examples of variation in raster angle (rendered by author using Solidworks)

The layer thickness, bead width, and air gap all refer to how lines of filament are laid in relation to one another. Layer thickness, or layer height, refers to the height of a line of filament deposited. Bead width (or road width or raster width) is the width of a cross sectional slicing of filament. Air gap is the amount of space in between lines of filament. Bead width and air gaps are products of infill settings, deposition temperature, and deposition speed. These quantities can all be seen in Figure 9.

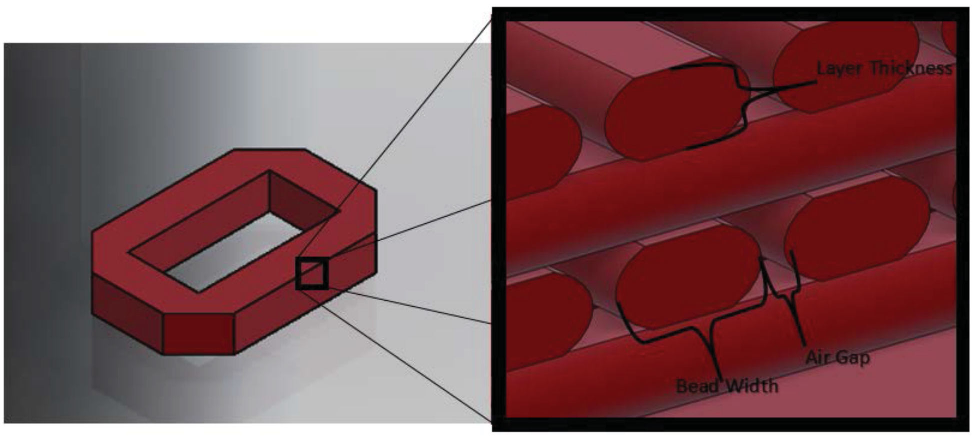


Figure 9. Examples of layer thickness, bead width, and air gap (rendered by author with Solidworks)

Table 8 summarizes experimental findings on how these parameters affect the mechanical properties of ABS parts created using FDM. Though less literature exists for FDM parts made with other plastics, it is presumable that these relationships hold for parts printed with PLA and other plastics. In Table 8 the plus sign (+) indicates a positive correlation between the parameter and mechanical property. The negative sign (-) indicates that the parameter and mechanical property are negatively correlated. The tilde (~) indicates that a relationship exists, but the correlation depends on multiple factors and may be either positive or negative. The circle (O) indicates that the study listed did not find an observable relationship.

Table 8. Summary of build parameters effects on mechanical properties based on literature

	Mechanical Property						
Parameter	**Tensile Strength**	**Compression Strength**	**Flexural Strength**	**Impact Strength**	**Fatigue**	**Wear Resistance**	**Stiffness**
Build Orientation (with respect to the direction of force applied)	~ (Raut,et al, 2014) (Bagsik and Schoppner 2011) (Durgun and Ertan 2014)	~ (Ahn et al 2002)	~ (Raut et al. 2014) (Durgun and Ertan 2014)	~ (Sood et al 2010)	~ (Lee and Huang 2011)	~ (Sood et al 2012)	~ (Tymrak 2013)
Raster Angles (with respect to the direction of force applied)	- (Durgun and Ertan 2014) (Ahn et al, 2002)	- (Sood et al., 2012) (Durgun and Ertan 2014)	~ (Durgun and Ertan 2014) (Ahn et al., 2002)	+ (Sood et al., 2010)	~ (Lee and Huang 2011)	- (Sood et al., 2012)	
Air Gap	- (Bagsik and Schoppner 2011) (Ahn et al., 2002)	- (Sood et al., 2012)	- (Sood et al., 2010)			+ (Sood et al., 2012)	- (Ahn et al., 2002)
Bead Width	O (Ahn et al., 2002)	O (Ang et al., 2006)		+ (Sood et al., 2010)		- (Sood et al., 2012)	
Temperature	O (Ahn et al., 2002)						
Layer Thickness	+ (Sood et al., 2010)	- (Sood et al., 2012)	- (Luzanin et al. 2014)	+ (Sood et al., 2010)		~ (Sood et al., 2012)	~ (Tymrak 2013)

Durability is another important factor in the success of parts made for the developing world, as the environment in which products are used is often rugged. For this reason, perceived durability is often a crucial component in product desirability to BOP consumers (Whitehead et al., 2014). Depending on the part, resistance to fatigue, impact strength, and the ability to resist wear are all mechanical characteristics that should be considered and are influenced by build parameters. Limited testing on FDM parts has been done concerning these quantities; however, the literature that does exist indicates that these strengths are also dependent upon the build parameters, as indicated in Table 8.

Products need not only to be durable, but also perceived to be durable (Whitehead et al., 2014). As most FDM products are plastic, some BOP users may find FDM parts less desirable if the part is traditionally made with other materials such as metals, wood, or ceramics. Most products in the developing world are repaired rather than replaced, and the difficulty of repairing a product is often on the forefront of many developing world consumer's minds (Whitehead et al., 2014).

For the sake of evaluating a product more effectively, finite element analysis should be conducted, keeping in mind the anisotropic mechanical properties of 3D-printed objects. However, for the purposes this paper, the maximum relevant stresses required of a product can be determined and compared to the 3D printing results seen from literature.

Feasibility Questions 6: What is the maximum tension strength required of this product?

The tension forces on a product should be considered in every direction and build orientation should maximize tensile strength in the direction where tension is expected to be highest. It should be noted that the tensile strengths of 3D printed parts are significantly less than those manufactured with other methods. For example, tests by Ahn et al. (2002) indicate that ABS 3D-printed parts only achieve strengths of 10-73% percent of comparable injection molded parts, depending on build parameters. As FDM parts are anisotropic, this maximum strength is still only achieved in one direction. Maximum and minimum tensile strengths achieved by ABS parts with FDM can be seen above in Table 7.

Studies at Michigan Technological University by Tymrak et al. (2014) support Ahn et al., (2002) but suggest that FDM parts made from PLA are able to achieve tensile strengths much closer to those of injection molded parts.

Feasibility Questions 7: What is the maximum compression strength required of this product?

As seen in Table 8, compressive strength is also dependent on a part's build orientation. The same study by Ahn et al. (2002) showed that the compressive strengths of ABS parts made with FDM are much more comparable to other manufacturing methods, with 80-90% of the compressive strength of similar injection molded parts. Additionally, studies by Percoco et al. (2012) show that the compressive strength of an ABS part made with FDM can be improved by post build treatments with acetone.

Feasibility Questions 8: What is the maximum flexural strength required of this product?

Flexural strength is affected by design decisions in a part’s internal geometry and can vary greatly. Examples of this range of strengths can be seen in Table 7 above. The study by Percoco et al. (2012) also indicates that ABS parts can attain improved flexural strength with post processing acetone treatments.

Feasibility Questions 9: What is the maximum stress due to impact this product will experience?

Limited tests have been conducted regarding the ability of an FDM part to resist impact; however, Sood et al. (2010) performed Charpy impact tests on FDM parts in order to determine the effects that build parameters have in this regard.

Feasibility Questions 10: What is the maximum fatigue strength required of this product?

Relatively few studies have been conducted regarding the ability of FDM parts to resist fatigue; however, a study by Leo and Huang (2011) was conducted regarding the effect that build orientation has on the tensile fatigue strength of FDM parts. More data regarding the ability of FDM parts to resist fatigue is necessary.

Feasibility Questions 11: What is the maximum wear resistance required of this product?

As also shown in Table 8, build parameters are even able to have significant effects on a printed part's ability to resist sliding wear (Sood et al., 2012). As surfaces of FDM surfaces can be quite rough depending on build parameters, the ability to resist wear can be important.

There are many other types of mechanical properties to take into account; however, literature regarding mechanical properties of FDM parts is still limited, and all properties will vary depending on build parameters. The overall strengths of parts can be further improved by different strategies like printing empty frames and filling the frames with resins. Though this technique remains largely unexplored and complicated for recycling, the limited results appear promising (Gorski et al., 2014).

Most FDM machines that are currently being used extensively and that are discussed for open source applications are not capable of manufacturing using multiple material types at once. Even when such machines have been available, there have been noted challenges in using multiple filaments on one print, even if both filaments are of the same material (Hergel and Lefebvre, 2014). For the duration of this report, only single material prints will be considered.

Feasibility Question 11: What resolution is required to manufacture this part?

3D-printed technologies are often lauded for their ability to manufacture complex geometries through no additional machining costs. The degree of accuracy and resolution, however, varies widely depending upon the settings and capabilities of the printer. Examples of this can be seen in Figure 10.

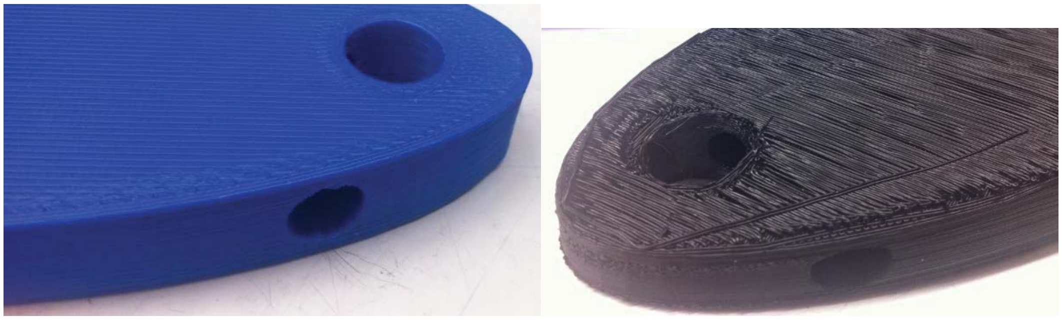


Figure 10. Variations in quality of a single part made on two different printers (Photo by author)

Required resolution should be specified in terms of millimeters, and build parameters can then be optimized according to Table 10 to achieve these resolutions. If a part requires resolutions more highly constrained than what the printer is capable of, as shown in Table 9, the use of 3D printing should be abandoned.

Table 9. Resolutions theoretically achievable with low cost 3D printers as adapted from Pirjan and Petrosanu (2013)

Printer	**Resolution**
Makerbot Replicator	0.2 mm
MakerGear Mosaic M1	0.15 mm
Ultimaker	0.04 mm
WhiteAntCNC	0.25 mm
PrintrBot	0.3 mm
RepRap Huxley	0.1 mm
PrusaMendel	0.1 mm
AO-100	0.1 mm

The texture of the part surface, the internal porosity of a part, and the level of dimensional accuracy achieved by a part are all dependent on build parameters similar to those parameters affecting a part's mechanical properties. The build parameters and related part qualities are compared in the Table 10. Table 10 utilizes the same coding as Table 8. Plus signs (+) indicate a positive correlation, negative signs (-) indicate a negative correlation, and a tilde (~) indicates that a relationship exists, but it is complex and the correlation may vary.

Table 10. Literature summary of build parameter's effects on part quality

	Part Quality		
Parameter	**Surface Roughness**	**Porosity**	**Dimensional Accuracy**
Build Orientation	~ (Durgun and Ertan 2012)		
Deposition Speed			- (Lanzotti et al., 2014)
Air Gap	+ (Arumaikkanu et al., 2005) (Nancharaiah et al., 2010)	+ (Ang et al.,2006)	
Bead Width	+ (Arumaikkanu et al. 2005) (Ahn et al., 2002) (Nancharaiah et al., 2010))	- (Arumaikkanu et al., 2005) (Ang, et al., 2006)	~ (Nancharaiah et al., 2010)
Temperature	- (Arumaikkanu et al., 2005)	- (Arumaikkann et al., 2005)	
Layer Thickness	+ (Nancharaiah et al., 2010)	+ (Arumaikkanu et al. 2005)	+ (Nancharaiah et al., 2010)

Feasibility Question 12: Does this product require a smooth finish or an airtight/watertight seal?

The accuracies achieved are sufficient for many applications; however, the surface quality is often lacking in FDM processes. Post processing chemical treatments are also often necessary if the part in question must be able to withstand pressure in regards to airtightness or watertightness (Mireles et al., 2011).

Due to imperfections in the manufacturing and the layered nature of the parts, post processing is also able to correct for surface roughness. This too, however, requires additional chemical treatments (Rao et al., 2012).

3.3 Viability

Even if a product is considered desirable and technologically feasible, it must also make good financial sense to begin producing it. Due to the nature of 3D printing, the cost per unit is generally constant regardless of the quantity produced. Unlike other manufacturing methods, with 3D printing a product can be evaluated for viability based on only one-time production. All relevant concerns can be scaled to the cost and potential profit of manufacturing a single product. Costs are not only measured in dollars, as time and energy usage are also critical factors in manufacturing viability.

3.3.1 Defining Viability

Viability refers to “understanding whether embracing a new technology or supporting a particular user need is truly aligned with the organization’s strategic objectives and competitive positioning” (Weiss, 2002). It is often concerned with the economics of a solution and, according to Brown (2009), whether it is “likely to become part of a sustainable business model”.

A product’s viability is dependent on the business and plan that accompanies a product’s design, and it determines if a product is able to be a profitable and worthwhile use of time, energy, and resources. For profit to be possible, the product must be desirable and feasible, and the consumer must be able to purchase it.

3.3.2 Considerations for the Evaluation of Viability

Most concerns regarding the viability of a 3D-printed product can be summarized by evaluating how much it costs to produce a single product and how much the customer is willing to pay. The latter concern hinges on desirability, as what a consumer is willing to pay is related to its perceived benefits (Lai, 1995).

Viability Question 1: How much does the product cost to make?

The basics of the cost to produce a single part, from the standpoint of someone operating a 3D printer, can be summed up by the Equation 3 from Mello et al. (2010).

$$\mathrm{C_{part}} = \mathrm{C_{pre}} + \mathrm{E_{total}} * \mathrm{C_{energy}} + \mathrm{m_{filament}} * \mathrm{C_{filament}} + \mathrm{C_{post}} \qquad \text{Equation 3}$$

where $\mathrm{C_{part}} = \text{total cost of part (USD)}$

$\mathrm{C_{pre}} = \text{pre} - \text{processing cost (USD)}$

$\mathrm{E_{total}} = \text{total energy used to operate printer (kWh)}$

$\mathrm{C_{energy}} = \text{cost of energy (USD/kWh)}$

$\mathrm{m_{filament}} = \text{mass of filament used (kg)}$

$\mathrm{C_{filament}} = \text{cost of filament (USD/kg)}$

$\mathrm{C_{post}} = \text{post} - \text{processing cost (USD)}$

This equation, of course, assumes that the purchase of the 3D printer, computer, and assembly costs are already accounted for. The preprocessing costs for 3D printing are often negligible from the standpoint of the printer. Assuming that materials and energy sources are ready for use once the build begins, the only remaining input is the CAD file. The CAD file for the print could be purchased, acquired through open source availability, or created in-house. In these cases, respectively, the costs are either the cost of the file, nothing, or the time of the operator and computer technician (Mello et al., 2010). For the purposes of this analysis, the pre-processing costs will be neglected.

The cost of material in manufacturing a 3D-printed object can be roughly calculated by knowing the volume of product to be produced. Printer filament is generally sold in terms of USD per kilogram, and, if the density of the material is known, the cost of the part can be approximated by knowing the volume of the part being printed. This is also because the costs associated with energy are still generally insignificant when compared to the cost associated with material (Kreiger et al., 2014). If one knows the mass of the filament needed to fill the volume of the product to be manufactured, a linear estimation between volume of product and the total cost of materials can be calculated using a relationship like Equation 4.

$$C_{part} = V_{part} * \rho_{filament} * C_{filament} \text{ (USD)} \qquad \text{Equation 4}$$

$$\text{where } V_{part} = \text{total geometric volume of the part } (mm^3)$$

$$\rho_{filament} = \text{density of filament material } (g/mm^3)$$

This assumption, however, is not entirely correct, as the volume of filament used is not the same as the volume of the part. A certain degree of porosity exists for a product made with FDM, as seen in Figure 11 below. This is largely due to the rounded cross sectional geometry of the filament. Voids occur that may vary in size due to both the build settings and design (El-Gizawy, 2011).

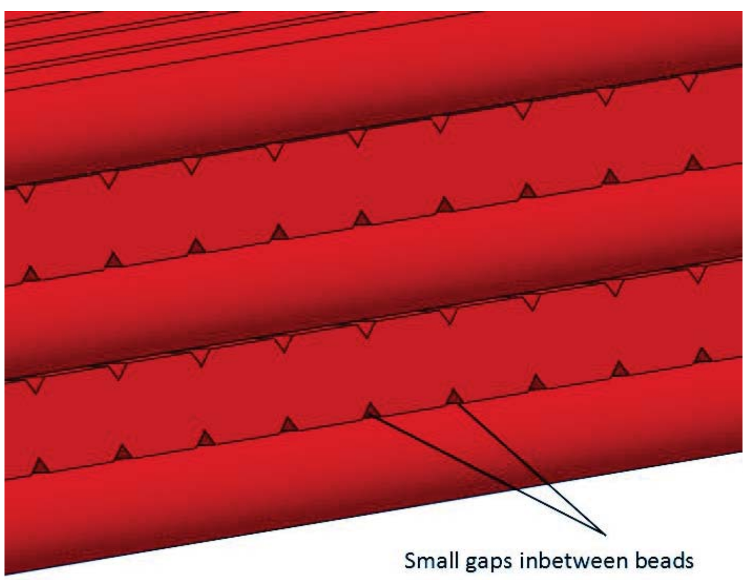


Figure 11. Porosity exists in all FDM parts (rendered by author using Solidworks)

To minimize material costs, to minimize product weight, or to alter other mechanical properties of a part, the amount of material used inside of a solid 3D-printed part is often altered (Lu et al., 2014). The amount of material removed can be determined during the printing process. By removing unnecessary infill in the CAD design, the amount of material used is reduced and therefore the cost is reduced. This is exemplified in Figure 12.

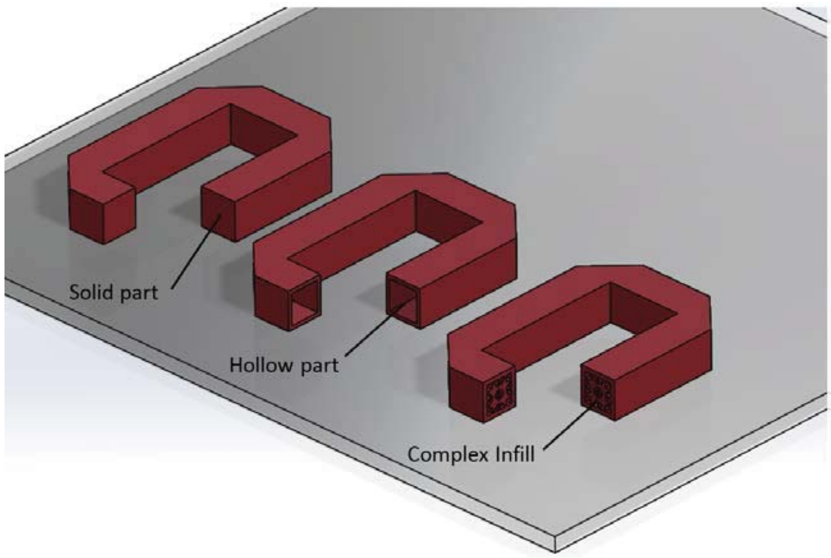


Figure 12. Variations in infill of a part can occur with no external evidence of process (rendered by author using Solidworks)

The thickness of the perimeter is not taken into account in the percentage infill. While for large objects this discrepancy is negligible, that is not the case for products that can be built within the build envelope of most open source 3D printers. It is at this point in the design process (or rather the printing process) that the geometry of an object affects its manufacturing. Contrary to most perceptions (Conner et al., 2014), complexity can affect the final cost of the product. If an object has a high surface area to volume ratio, its ability to benefit from infill reduction is reduced. Additionally, if an object is complex with more concave or overhanging features, it will have a higher need for structural support (Stava et al., 2012).

However, if the actual volume of filament used can be predicted, then the cost can be estimated with accuracy using Equation 5 and methodologies for calculating the volume of a filament, $V_{filament}$,.from the volume of any part, V_{part} are located in Appendix A.

$$C_{part} \approx V_{filament} * \rho_{filament} * C_{filament} \text{ (USD)} \qquad \text{Equation 5}$$

where $V_{filament}$ = the filament used to produce the part (mm^3)

Data was acquired from past studies conducted at Michigan Technological University to compare the volumes of 3D-printed parts to their costs (Kreiger et al., 2014). In Figure 13 it can be seen that the cost to produce a 3D-printed part is almost entirely dependent upon the amount of filament used as energy costs vary nearly linearly with the volume of filament (Kreiger et al., 2014). Equation 5 is far more effective than Equation 4 in predicting the total cost of the product or part.

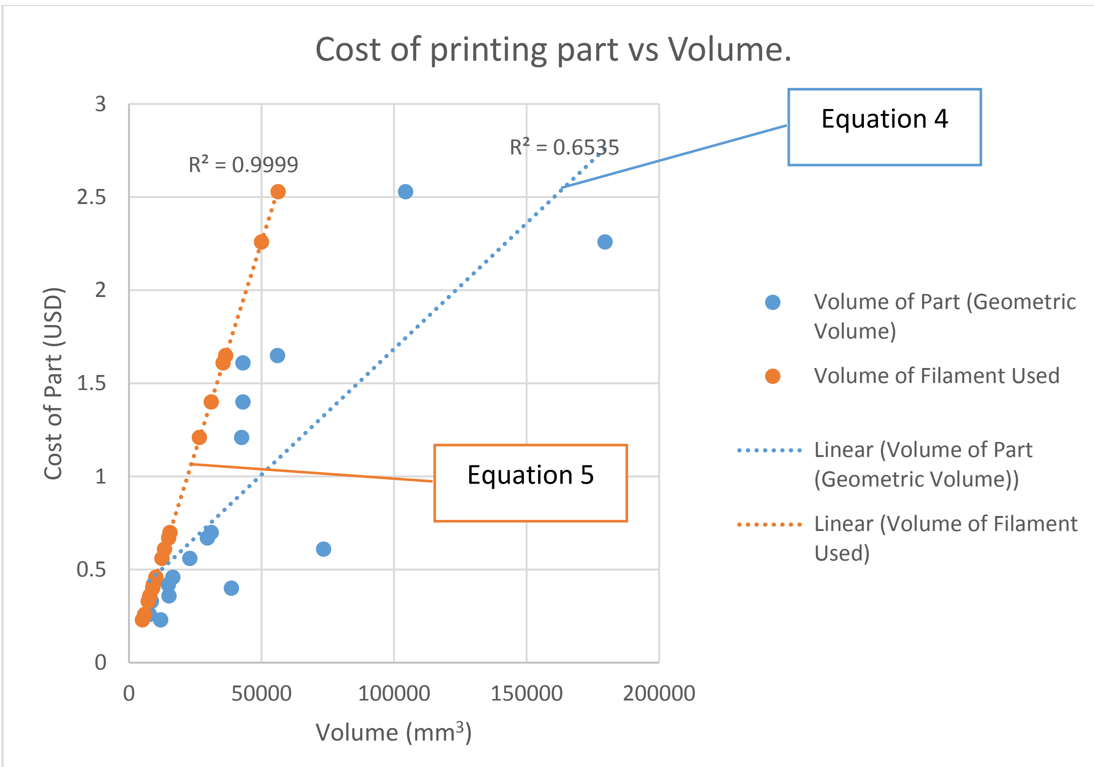


Figure 13. Comparison of filament and geometric volumes ability to predict cost (adapted from Kreiger et al., 2014)

However, predicting the volume of the filament of an object based upon its geometric volume is not simple. Variations in geometry may not directly influence a part's cost to be 3D printed; however, variations in surface area to volume ratio from part to part can significantly affect a part's ability to benefit from infill reduction and the volume of filament used. This is shown in Figure 14 where the actual volume of filament used for a part varied more greatly when parts have reduced infills, and the volume of filament used can be accurately known if the infill is at its maximum.

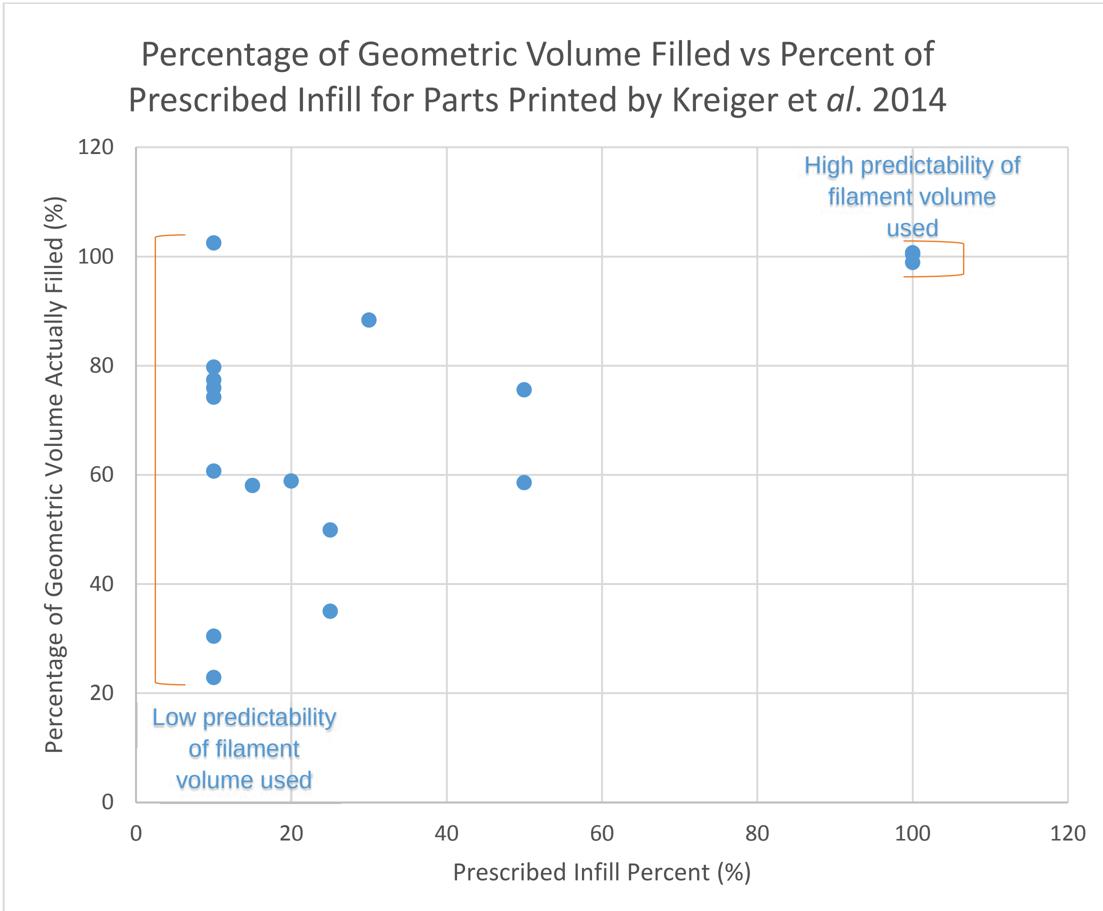


Figure 14. Ability to predict the volume of filament used diminishes with the reduction of infill [adapted from Kreiger et al. (2014)]

It can also be noted in Figure 14 that the ability to predict the volume of a filament used diminishes as the infill of a part is reduced. Methodologies for calculating the volume of filament necessary to print a part can be used, and several methods are presented in Appendix A of this report. Slicing software is able to make fairly accurate predictions of filament needed (Kreiger et al., 2014). It should be noted that while this uncertainty is especially important to deal with when manufacturing a large quantity of products, 3D printing does not require that large quantities of products be manufactured to be viable.

The ability to keep low inventory is a potentially important factor for BOP entrepreneurs, as many shop owners may not be able to maintain or afford the capital necessary to maintain a high inventory. Because distributed manufacturing with 3D printing has the ability to reduce costs associated with inventory and shipping, it is often proposed that manufacturing locally could reduce the cost of production (Nyman and Sarlin, 2014).

Theoretically, the labor costs required to print a part could be nearly negligible as an ideal 3D printing system could include a point-and-click method of printing objects from CAD files. However, maintenance and post-processing will still require labor and will incur some labor costs.

Viability Question 2: What are people able to pay for this product?

Regarding consumer spending ability, it has been seen that though East African economies are often financially constrained, most people still have some discretionary income to spend and the ability to make purchasing decisions beyond necessities (Hammond, 2007; Banerjaree and Duflo, 2007). One potentially effective method of determining a starting price would be to find the prices of similar products currently being sold that do not utilize 3D printing. Once the costs of manufacturing a product with 3D printing are known, these costs can be compared to the cost of objects that currently exist and that are able to perform the same function.

As mentioned when discussing viability, there are three ways a product can stay competitive-cost leadership, differentiation from competition, and customization (United Nations Environment Programme, 2009). Thus, if 3D printing can enable lower costs of producing a product without sacrificing desirability, much could be gained in regards to viability. It is reasonable to believe from past studies that 3D printing typically can provide a cheaper alternative for the manufacturing of many products (Kreiger et al., 2014).

Viability Question 3: How much time does it take to produce the product?

It is also required to take manufacturing time into consideration when evaluating the economic viability of producing an object through 3D printing. If it takes a long time to manufacture a product, even at low cost, it may not be a viable product.

The amount of time needed to produce a 3D-printed object would also depend on the geometric volume of the object. For the same reasons outlined with respect to material cost, this is not exactly the case, and it is far more accurate to estimate the amount of time needed for manufacturing based on the amount of filament used. The formulas needed to estimate the time associated with 3D printing can be found in work by Alexander et al. (1997), and these formulas are given in Equation 6, Equation 7, and Equation 8.

$$\mathrm{t_{part}} = \mathrm{t_{pre}} + \mathrm{t_{build}} + \mathrm{t_{post}} \quad \text{(s)} \qquad \text{Equation 6}$$

where $\mathrm{t_{part}}$ = time required to manufacture a part with 3D printing (seconds)

$\mathrm{t_{pre}}$ = time for preprocessing (s)

$\mathrm{t_{build}}$ = time for build (s)

$\mathrm{t_{post}}$ = time for postprocessing (s)

The build time, $\mathrm{t_{build}}$, .for any FDM process can be summed up by Equation 5.

$$\mathrm{t_{build}} = \mathrm{t_{warmup}} + \mathrm{t_{deposition}} + \mathrm{t_{z}} + \mathrm{t_{clean}} \quad \text{(s)} \qquad \text{Equation 7}$$

where $\mathrm{t_{warmup}}$ = time required for the printer to warm up (s)

$\mathrm{t_{deposition}}$ = time of actual deposition of filament (s)

$\mathrm{t_{zadjust}}$ = time for adjustment of nozzle along z − axis (s)

$\mathrm{t_{clean}}$ = time for cleaning of nozzle (s)

The majority of the build time resides in the warm up and deposition time (Yoon et al., 2014), and the warm up time is generally dependent upon the printer model and the ambient temperature (Yoon et al., 2014) and not the part itself. Actual build time, can roughly be considered a function of the volume of filament used and the flow rate of the machine (Alexander et al., 1997).

As the flow rate is controllable within the build parameters, the volume of filament needed remains the primary variable in determining the necessary time for printing as seen in Equation 8.

$$t_{deposition} = \frac{V_{filament}}{Q} \qquad \text{Equation 8}$$

where $Q =$ flowrate at nozzle (mm^3/s)

$V_{filament} =$ the filament used to produce the part (mm^3)

It should be noted that the machine being used and the print parameters will also affect the amount of time it takes to build a part.

For the product to be viable a seller must be able to manufacture enough of the product over the course of a day to be profitable. However, unlike other machining operations, the operator for a FDM machine generally does not need to be present and therefore build time does not necessitate man-hours. Other income generating activities could simultaneously be undertaken.

Viability Question 4: What are the energy and energy cost demands of producing this product?

While this will further be discussed in other sections, many parts of the developing world have little to no access to an electrical grid. The people that do have grid access often find grids that are unreliable and often fail to provide power. If the printer being used is unable to operate after an electrical surge or cannot resume a print once power resumes, it will be difficult to manufacture products that require more time and energy to manufacture.

The energy costs of a product are dependent upon the size of the product, the materials of the product and, once again, its geometric complexity. The energy required can be calculated by Equation 9.

$$E_{part} = P_{warmup} * t_{warmup} + P_{build} * t_{build} \qquad \text{Equation 9}$$

where $P_{warmup} = \text{power used during warmup phase (kW)}$

$$P_{build} = \text{power used during warmup phase (kW)}$$

It should be noted that the energy use during warmup is not negligible and can comprise over half of the total energy used in the printing process (Walls et al., 2012; Yoon et al., 2014).

It was also alluded to earlier that energy sources and their reliability are often a significant factor in the developing world. If the amount of energy needed to produce a particular product exceeds what is available, the product may not even be considered feasible, let alone viable. It should be noted that the amount of power needed to manufacture a product can also be affected by the power requirements of the printer being used (Yoon et al., 2014, Walls et al., 2012).

3.4 Summarizing Questions Related to Human-centered Design

Given the considerations discussed thus far, there exist a number of criteria that can be used to evaluate a product's potential desirability, feasibility, and viability.

First one must determine if the product already has a demonstrated desirability within its market, and then questions should be asked to determine if an alternative created through 3D printing could be made to be more desirable. A summary of the questions regarding desirability can be seen in Table 11.

Table 11. Summarizing questions to consider in regards to desirability

Questions		**Measurement**
1.	Has the desirability of this product already been demonstrated through a comparable product in the market?	Units/(Consumer*year)
2.	Will the perceived value of an existing product be increased in relation to its cost by manufacturing it through 3D printing?	Total benefit

It is difficult to quantify the desirability of an object, and more research is needed to be able to understand what is desirable within a specific culture.

After considerations of desirability, one must determine the feasibility of a product for developing world markets. It is possible to quantify the constraints of a product needed to achieve functionality, and then compare these to what is achievable by FDM parts and printers. It should be kept in mind that FDM parts are generally weaker than parts made by other manufacturing methods. Additionally, their mechanical properties are anisotropic, and the maximum achievable strengths are only in the build direction that optimizes the strength of a part. Both the strength limitations and the understanding of the mechanical properties could prove to be some of the more significant hurdles to surmount when considering the use of 3D-printed parts in the developing world. A summary of the questions regarding the feasibility of a product can be seen in Table 12.

Table 12. Summarizing questions to consider in regards to feasibility

Questions		Measurement
1.	Does this part have complex geometry that could not be achieved with other manufacturing methods?	yes/no
2.	What is the build envelope of the product?	mm x mm x mm
3.	What level of customizability is required?	0-4 (Connor et al., 2014)
4.	Does the product's function benefit from having a specified density?	yes/no
5.	What is the maximum temperatures to which this product will be exposed?	C
6.	What is the maximum stress due to tension this product will experience?	N/mm^2
7.	What is the maximum stress due to compression this product will experience?	N/mm^2
8.	What is the maximum stress due to flex this product will experience?	N/mm^2
9.	What is the maximum stress due to impact this product will experience?	N/mm^2
10.	What is the ultimate stress associated with fatigue this product will experience?	N/mm^2
11.	What is this product's ability to resist wear?	mm^3/m
12.	What print resolution is required to manufacture this part?	mm
13.	Does the part require a water tight seal?	yes/no

If a product is deemed to be desirable to consumers and technologically feasible, it can then be evaluated for financial viability. 3D printing is relatively unique because viability can be assessed on a print by print basis. By determining the cost of producing a product and the potential price of the product, one can easily calculate the potential profit available per unit manufactured. These values are all instrumental in determining the viability of a product and can be seen in Table 13. However, actual recommendations as to whether or not they can be produced depend upon individual business models. This will further be explored in Section 4.

Table 13. Summarizing questions to consider regarding viability

Questions		**Measurement**
1.	How much does the product cost to make?	USD
2.	What are people able to pay for this product?	USD
3.	How much time does it take to produce the product?	min
4.	What are the energy and energy cost demands of producing this product?	kWh, USD

4.0 Sustainability

For the purposes of this paper, sustainability will be defined using the Brundtland commission definition, as the ability "to provide for the needs of the current generation without compromising the needs of future generations" (Brundtland, 1987).

When designing products that are to benefit those living in developing countries it is also important to consider the sustainability of a product. All sustainability concerns are centered on the patterns of production and consumption that humans engage in, and if sustainability is to be achieved, it is necessary to develop more effective ways to provide both goods and services to people worldwide (Castillo et al., 2012). This will come from the efforts of improving design, manufacturing, and consumption patterns (Melles, 2011). Designers and manufacturers have a moral and ethical duty to be responsible for the sustainability of their products (Diegel et al., 2013), maximizing a product's value while minimizing the resources the product consumes (Fiksel et al., 1998).

Sustainable design includes sustainability in regards to the wellbeing of humanity, economy, and environment (United Nations Environment Programme, 2009). The success of a product should be evaluated with both the human-centered design criteria and all three aspects of sustainability in order to see what a product's impact will be on the development of a region. Thus, human-centered design and three-tier sustainability are two sets of criteria that could be viewed as interrelated. Human-centered design looks at evaluating whether or not a product is successful today, and sustainability primarily assesses what its impact will be tomorrow. It is not difficult to see how human-centered design and sustainability concepts overlap. For example:

> -If a product is to be desirable for tomorrow it must be largely be beneficial to the economy and humanity both today and tomorrow.
>
> -A product cannot be economically sustainable if it is not first viable (Ljungberg, 2007).

-If a product is to be viable both today and tomorrow it must make efficient use of economic and environmental resources.

-If a product is desirable it is often more environmentally sustainable, as it will have a longer life-cycle (Diegel et al., 2010).

These questions are valuable for decisions made in regards to the entire ecosystem surrounding a product and can be used to assess the total impact that the 3D printing of a product has on a society, its economy, and the environment for both current and future generations. Although these questions should be asked before a product is manufactured, these criteria can also be used for the ongoing assessment of a product that is already being manufactured. Thus, sustainability in regards to social, economic, and environmental concerns will all be applied in the evaluation of 3D-printed products and their manufacturing.

4.1 Social Sustainability

Social sustainability is the aspect of sustainability that is on the forefront of most development initiatives as social issues are often the most visible and pressing. Some goals of social sustainability include: elimination of hunger, health care access for all, safety, equitable education, and equitable employment (Sustainable Development, 2015).

4.1.1 Defining Social Sustainability

There are not universally agreed upon guidelines for what defines a socially sustainable product (Fiksel et al., 1998). A product's entire life-cycle, especially manufacturing, is important when considering sustainability. General categories of social sustainability concerns with manufacturing include- the improvement of human rights for workers, reduction in unfair or child labor, health and safety in the workplace, abolishing of corruption and bribery, community development, and increased stakeholder engagement (United Nations Environment Programme, 2009).

4.1.2 Considerations for Evaluating a Product's Social Sustainability

Distributed manufacturing with 3D printing promises to make changes in how consumer goods are both produced and acquired. Most of these changes are expected to promote equity by diversifying who has ownership of manufacturing assets and focusing on developing a community's indigenous social and material capital (United Nations Environment Programme, 2009). Moving centers of production to the location of consumers would involve some disruption in normal supply chains, as the advantages of being able to manufacture *en masse* in emerging countries (i.e., China or India) becomes less significant. Working conditions in these settings often fail to meet the standards of human rights of the people working in manufacturing, and it is important to consider whether or not 3D-printed products could place similar burdens on those involved with their manufacturing. The first concern to address regarding social sustainability will be the safety of manufacturing a product.

Social Sustainability Question 1: What are the total chemical hazards involved in the manufacturing of this product?

Generally, there are few hazards associated with 3D printing. Most of the risks associated with subtractive machining process are not present, as no cutting or cutting fluids are involved in 3D printing (Huang et al., 2013; Faludi et al., 2015). As the build process is largely automated, the labor all comes from the pre and post processing procedures. Pre-processing mostly involves only CAD design work and basic machine maintenance. Post-processing involves a few potential health hazards including sanding (Faludi et al., 2015) and chemical treatments for altering and finishing the surface texture (Rao et al., and Ojha, 2012). For example, acetone vapor is a commonly used method of treating ABS parts and while it is not exceptionally toxic (Fisher Scientific, 2009), acetone is an irritant to both breathing and the eyes. From the author's personal experience, it has been observed that a general respect of chemical hazards does not exist in the Tanzania, and it is possible that this trend extends to other developing countries. Such lack of appropriate caution is probably due a need for education, and thus every potential chemical hazard should be regarded as a serious chemical hazard. Chemical treatments are not required for every FDM part, however, and can be avoided if there are no special surface texture requirements.

It has been shown that printers using PLA or ABS do give off emissions of ultra-fine particles while in use (Stephens et al., 2013), and these emissions are mostly due to the heating of the plastic. Particularly when dealing with ABS, fumes can contain small amounts of hydrogen cyanide and carbon monoxide (Rutkowski and Levin, 1986), and thus it is best to conduct printing in a well vented area (Stephens et al., 2013). Based on the experience of the author, such precautions are often disregarded by those working in the developing world. The author attributes this phenomenon to not being able to see immediate effects of harmful practices, often relegating safety as unnecessary in the eyes of East African tradesmen. (For example, many arc welders can be observed practicing their craft on the streets without safety goggles or gloves.)

Other than small concerns of air quality and potential chemical treatments, there are few foreseeable health concerns as the process of 3D printing is largely automated. However, any discussions concerning the sustainability of 3D printing must include the entire life-cycle, and the effects of manufacturing the filament must also be taken into account. If 3D printing becomes a viable manufacturing method, there will be an increased demand for printer filament worldwide, and the wellbeing of the people involved with the manufacturing of filament must also be considered. It has been suggested that potential for abuse of human rights will exist, if not at the product manufacturing stage, then at the filament production stage. Thus, industry standards should be adopted to protect those who work in filament production (Feeley et al., 2014). These standards apply to both models of producing virgin filament and recycled filaments, and are given in Table 14

Table 14. Socially sustainable production of printer filament measures proposed by Feeley et al., (2014).

Standards for an ethical production and trade of recycled 3D printer filament	
1	Minimum wages must be established to ensure that plastic salvagers are compensated fairly.
2	Fair trade premium prices could be charge with the additional profits being used to reinvest in development where filament production occurs.
3	International labor standards specific to plastic salvagers should be implemented.
4	Environmental impacts should be minimized by technological improvements to plastic recycling technology.
5	Plastic recycling groups should ensure that all filament producing equipment is safe and clean to operate.
6	Companies should use equitable employment practices for all involved in the filament recycling process.

There is an additional concern that is widespread concerning the safety of 3D printing, and this concern is the ability of a printer to print weapons or other dangerous materials (Pirjan and Petrosanu, 2013). All that is necessary to print something harmful is a feasible CAD design, and while methods of preventing such uses have been discussed, it will ultimately be difficult to control what a printer is used for.

Alternatively, products that can benefit humanity could be considered socially sustainable. One of the more agreed upon criteria for creating a socially sustainable product is one that empowers the user to improve their social or economic status (Melles et al., 2011; Donaldson, 2009). Products that promote social sustainability could include personal medical devices, educational materials and agricultural tools, among many others. While economics may drive the need for most products, the necessity of some products may not be reflected in the quantity of their demand. For example, medical products can be difficult to acquire in rural hospital settings due to their low volume and high prices. The low demand, however, does not diminish their importance.

In order to determine suitable qualifications, this paper will look to the Sustainable Development Goals (SDG). The SDG are a proposed set of goals that are to replace the Millennium Development Goals, set to be reviewed later this year and proposed to help define where sustainability efforts should be directed post 2015 (Sustainable

Development, 2015). If a product can be linked to meeting any of these criteria developed by the United Nations, the product could be considered to be beneficial to humanity and socially sustainable.

Social Sustainability Question 2: How many of the Sustainable Development Goals are promoted by printing this product?

Food security, human health, gender equity, water and sanitation access, and education are all social focuses of the Sustainable Development goals. If a product is able to directly assist in the attainment of goals in these areas, it could be considered a more socially sustainable product. The Sustainable Development Goals can be seen in Table 15.

Table 15. Proposed Sustainable Development Goals (Sustainable Development, 2015)

Goal	Sustainable Development Goals
1	End poverty in all its forms everywhere
2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3	Ensure healthy lived and promote well-being for all at all ages
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	Ensure availability and sustainable management of water and sanitation for all
7	Ensure access to affordable, reliable, sustainable and modern energy for all
8	Promote sustained, inclusive, and sustainable economic growth, full and productive employment and decent work for all
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
10	Reduce inequality within and among countries
11	Make cities and human settlements inclusive, safe, resilient and sustainable
12	Ensure sustainable consumption and production patterns
13	Take urgent action to combat climate change and its impacts
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

(retrieved from https://sustainabledevelopment.un.org/sdgsproposal)

The process of printing, regardless of product, could promote self-sufficiency as well. Distributed manufacturing could provide more educational and trade-skill enhancement opportunities for self-empowerment (Pearce et al., 2010). However, if skill sets are not developed alongside the acquisition of the technology, increased dependency could result from lack of knowledge concerning how to operate and repair 3D printers.

Social Sustainability Question 3: Does producing this product require technical knowledge that is unavailable to the users?

A strength of 3D printing is the ability to manufacture products customized for the user. However, given the current status of the technology, it requires in-depth knowledge of CAD and slicing software to be able to modify and customize parts. The lack of education in using such software could increase the dependency of local manufacturers on outside assistance, therefore reducing self-sufficiency. This is especially true if a product requires CAD customization or printer modifications that could make the product more complicated to produce. If the operator of a 3D printer is not able to print the product as necessary, either the education of the user or the usability of technology must grow to close this gap.

Social Sustainability Question 4: Does producing this product by 3D printing reduce wasted human capital?

Not fully utilizing design ideas of local manufacturers can be considered a form of human waste (Nyman and Sarlin, 2014), and because 3D printing allows for manufacturing and rapid prototyping to occur, general creativity can be more thoroughly utilized and new ideas could theoretically be explored.

The ability to better utilize creativity may not be seen immediately with application, however. As mentioned, revolutionary design and experimentation thinking is not often seen in the context of East African culture (Donaldson, 2009) and education in the effective use of CAD software would be necessary steps before this potential benefit to social sustainability could be employed.

3D printing could also promote gender equity in the workforce. For one example, in Tanzania, women generally do not participate in local manufacturing activities. Though clothing and small craft work is often permissible, carpentry, metalworking, and other local production means are generally seen as strictly masculine. Localized 3D printing, however, may not fall into standard gender role occupations and could be perceived to be a culturally appropriate occupation for women as well as men. Print shops are currently small businesses often run by women in Tanzania. As only 4.5% of small manufacturing business owners in TZ are currently women (Mahemba and Bruijn, 2003), 3D printing could provide opportunities that women have previously not had in manufacturing due to cultural barriers.

Social Sustainability Question 5: What is the total amount of man-hours of saved by the end user by producing this product locally?

Producing a product through distributed 3D printing could potentially decrease the number of man-hours used in procuring a product. If a product can be manufactured locally, the time needed to travel long distances to procure specialty products can be considered an increase in available man-hours.

A mentioned, 3D printing is largely automated, and thus manufacturing with 3D printing requires little labor. The amount of worker time used in manufacturing is significantly reduced when using 3D printing over other manufacturing techniques (Faludi et al., 2015).

4.2 Economic Sustainability

Social sustainability is not possible without economic sustainability. An economically sustainable product is one that looks beyond viability to understand what place the product holds and will hold within its marketplace.

4.2.1 Defining Economic Sustainability

Economic development is a key part of assessing the impact of any product in the developing world, as the economies of the BOP increasingly want to engage in global markets, not as passive clients, but as co-producers (Gwamuri et al., 2014). Sustainable economic development can be promoted by creating new jobs, opportunities for entrepreneurial growth, opportunities for business ownership, increasing fair trade opportunities, and increasing the productive output of individuals (United Nations Environment Programme, 2009).

As with many of the criteria examined thus far, there is much overlap between concerns of human-centered design and sustainability. A product's economic sustainability is highly dependent on its economic viability in the short term (Ljungberg, 2007) and its social sustainability in the long run.

4.2.2 Considerations for Evaluating a Product's Economic Sustainability

Distributed 3D printing in often regarded as being able to promote local economies by moving manufacturing to take place within the economy (Gwamuri et al., 2014). A flexible manufacturing system without extremely high cost, like 3D printing, could promote more entrepreneurial activities (Gebler et al., 2014). Local entrepreneurs can have a distinct advantage over centralized manufacturing groups because they are able to know their markets better and understand how to customize products for the people they are close to (Gebler et al., 2014).

As noted earlier, 12.3% of all Tanzanians regard their primary occupation as being small-business owners (National Bureau of Statistics, 2013), and 50% of all goods produced from within Tanzania are from these small-medium sized enterprises (Mahemba and Bruijn, 2003). Thus, the entrepreneurs already have a defined presence within the culture. It is through small enterprises that 3D printing has the most potential to be active as such companies are the most agile, flexible, and able to adopt innovation (Mahemba and Bruijn, 2003). This may be a challenge, however, as the presence of entrepreneurs does not necessarily equate to an openness to 3D printing. A study conducted regarding small businesses in Tanzania has shown that along with a lack of large innovation changes, small enterprises in Tanzania are hesitant to embrace new tools and equipment (Mahemba and Bruijn, 2003).

Centralized manufacturing methods have important advantages as they have access to employee specialization, capital, marketing, bulk purchasing, and better ability to invest in equipment (Kreiger and Pearce, 2013). Costs associated with manufacturing a product with 3D printing are generally higher per unit than other manufacturing methods (Kreiger and Pearce, 2013). However, for products manufactured at small or medium volumes, it may be more cost-effective to use 3D printing (Hopkinson et al., 2006). If customization is not required, the product can be evaluated solely in terms of quantity needed, and the breakeven point can be found (Conner et al., 2014). An example of determining the breakeven point of a product can be seen in Figure 15. This example illustrates how 3D printing is typically more economical than most other manufacturing methods when producing small batches of a product. The cost per item does not vary with quantity after initial machinery investments are made with 3D printing, whereas injection molding requires a new mold to be purchased for each different part (Huang et al., 2013).

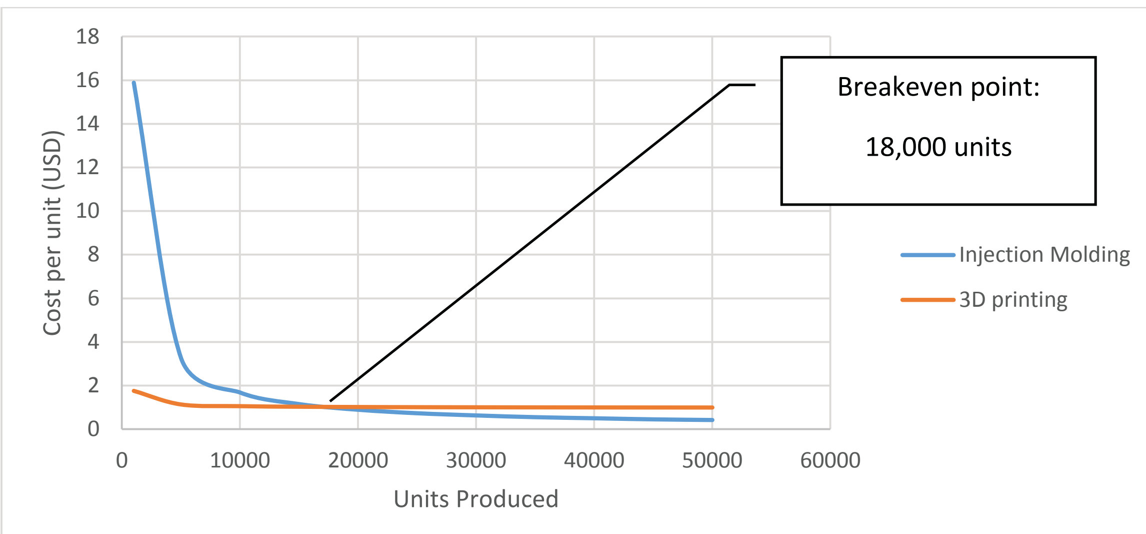


Figure 15. Example breakeven point between manufacturing methods for a hypothetical product after initial machinery investments (made by author with data from MIT 2015).

Economic Sustainability Question 1: How many units of this product must be made before it is more cost effective to manufacture through other techniques?

In order to determine if it is economically sustainable to produce a product locally, the breakeven point should be calculated and compared to the quantity of the product that will be manufactured. Calculating the cost of each part based on 3D printing may be done using the criteria outlined in the viability section of this report. Results of comparisons of manufacturing with 3D printing to other manufacturing methods depends entirely on the manufacturing technology that is being used.

However, even if a product does not require customization and is cheaper to manufacture by using manufacturing methods other than 3D printing, the startup capital required for mass manufacturing may not be attainable by entrepreneurs in the BOP. The credit and large investments that would be needed are generally not as readily employed in Sub-Saharan Africa as they are in western markets (Hattingh et al., 2012).

While initial costs of 3D printing equipment can be less than other manufacturing machinery, the cost can still be prohibitive to many people in both the developed world and developing world (Huang et al., 2013). However, this may not always be the case, and the price of 3D printers is on the decline according to Pirjan and Petrosnau (2013). A comparison of low cost 3D printers can be seen with Table 16.

Table 16. Comparison of low cost printer prices from Pirjan and Petrosanu (2013)

Printer	**Price (2013 USD)**
Makerbot Replicator	$1660
MakerGear Mosaic M1	$820
Ultimaker	$1500
PrintrBot	$540
RepRap Huxley	$540
PrusaMendel	$780
AO-100	$1420

With loans and micro financing, it is possible that entrepreneurs could afford printers at their current prices. However, such an individual would have to regard the printer as an investment, and formal credit and debt structures have generally not been commonly embraced concepts in East African culture (Hattingh et al., 2012). Once the initial investment is made, 3D printers generally have small additional costs, with nearly all costs beyond the printer being materials (Huang et al., 2013.)

When estimating the economic sustainability of producing a product with using 3D printing, it becomes no longer sufficient to examine only the viability of producing a single product. While this is outside the scope of this paper, evaluating the economic sustainability of a part also requires considering how the part could fit into the business model.

Economic Sustainability Question 2: Does manufacturing this product with 3D printing employ additional people or improve work opportunities for people within the community?

The ability to manufacture a specific part close to the source of need could potentially improve the overall economic output of a region because spare parts and products could be made on-demand. Moving centers of manufacturing to be local, more job opportunities could become available in the local community (Kohtala, 2014). Not only will printer owners gain more opportunity for self-employment, but people who salvage waste plastic will also have the potential for increased income.

Solid wastes, including plastics, are prevalent in the developing world as few countries have adequately developed recycling or waste collection systems, and in most rural areas of Africa such systems are non-existent (United Nations Economic Commission for Africa, 2012). Many urban areas have developed a sub-economy of people who make a living by salvaging plastic from urban waste (United Nations Economic Commission for Africa, 2012; Okot-Okumu, 2012). This collected plastic has been used for a variety of manufacturing purposes such as manufacturing of clothing from PET (Tierney, 2014). Machines like Recyclebot are able to accompany 3D printers to recycle waste plastic into useable filament for 3D printing (Baechler et al., 2013). In India, companies like

Protoprint have developed business models to create filament from used HDPE. Their business model allows them to be able to pay salvagers adequate wages and still sell filament for prices lower than most alternative sources of filament (Thoppil, 2014). The employment created by such ventures adds value to what was formerly a waste product and can stimulate local economies and provide job opportunities that were previously nonexistent (United Nations Economic Commission for Africa, 2012). It should be noted again that it is important to develop ethical standards for this ecosystem as such recycling would otherwise have the potential for human rights abuses. Salvagers are generally marginalized groups and have risky jobs, being exposed to a variety of dangerous materials (United Nations Economic Commission for Africa, 2012).

3D printing has the ability to disrupt and redistribute supply chains, altering economic power and profit centers by placing them in the communities in which the manufacturing takes place (Pirijam and Pertrosanu, 2013; Beyer, 2014). Thus, considerations should be given to what effects such disruptions will have on existing supply chains. As noted, Tanzania's primary import is consumer goods from China and India (CIA, 2014). If the product is able to be manufactured locally, the product will certainly affect the demand and load placed on international producers. Some BOP members are a part of these supply chains, and their livelihood may be affected for better or worse by such changes. It is important to consider how these factors will interact, though that is outside the scope of this paper.

Another common indicator of sustainable development is increased participation in global markets (United Nations Environment Program, 2009). Distributed manufacturing will undoubtedly affect this, but exactly how remains to be seen. While local production would reduce the import of some consumer goods, a developing country's global trade patterns could shift due to increased importing of new materials like printer filament (Pirjan and Petrosanu, 2013). These shifts in economy on a national scale are also outside of the scope of this report.

Economic Sustainability Question 3: How much material waste is reduced by manufacturing this product with 3D printing?

As with other aspects of sustainability, a key factor in determining the suitability of manufacturing a product through distributed 3D printing is its ability to reduce waste. The ability to reduce waste and demand for raw resources through leaner manufacturing techniques is clear advantage of 3D printing (Huang et al., 2013). As no cutting is involved, the amount of wasted scrap is almost zero in AM manufacturing activities (Pirjan and Petrosanu, 2013). Because fewer materials need to be used with 3D printing, 3D-printed objects can have complex geometries as a single piece, and one can often design around typical assembly requirements such as needing fasteners (Campbell et al., 2013). Also, AM methods have the ability to reduce material use by reducing the infill of a product (Kreiger and Pearce, 2013). As seen earlier in Figure 6, a product can be made using only the amount of material absolutely necessary to achieve functionality. Thus, while materials for 3D printing are more expensive, the reduction of waste generally offsets this cost (Gebler et al., 2014).

In some instances centrally manufactured goods can be too expensive for people in developing communities to afford (Gwamuri et al., 2014). Logistics of distributing goods to isolated and rural areas, often makes mass manufactured goods potentially more expensive than they would be if manufactured locally (Gwamuri et al., 2014), particularly in rural areas. Overall distribution costs are often cheaper with local manufacturing (Gwamuri et al., 2014), due to the shorter distances goods are transported after manufacture.

Economic Sustainability Question 4: How much can transportations costs be reduced by manufacturing this product locally?

Transportation costs can also be reduced when reducing the infill, as it reduces the weight of products (Beyer, 2014). Raw materials will still need to be shipped, but by shipping only spools of filament with high mass to volume ratio and little packaging compared to other products, transport costs could be reduced (Tatham et al., 2014).

Economic waste can be reduced in the form of less overproduction, less inventory, and less transportation (Nyman and Sarlin, 2014). 3D printing is able to reduce waste tied up in inventory costs (Huang et al., 2013), which can be significant for small business owners in the BOP with small capital. Only manufacturing of a needed part occurs with 3D printing (Diegel et al., 2010), and any spare part can be manufactured rather than purchasing an entire new assembly (Pirjan and Petrosanu, 2013; Wittbrodt et al., 2013).

4.3 Environmental Sustainability

Much discussion of development revolves around improving social wellbeing and economic wellbeing. While the environmental aspects of sustainable development are often not as readily apparent as the need for current social and economic issues, it is important that all aspects of development take into account the future of the community, nation, and the planet, as well as the community's current challenges. Based on the author's observations, this foresight is especially necessary for environmental sustainability, as few in the BOP are generally concerned with current environmental issues.

All three aspects of sustainability are strongly linked. Polak (2010) suggests that not only is the environment a key part of being able to improve human wellbeing, but also that economic and social development are key aspects of being able to improve the environment. His argument states that reduction in poverty and improvement in societal wellbeing can decrease a number of environmentally harmful activities such as warfare, deforestation, and unsustainable hunting practices (Polack, 2010).

4.3.1 Defining Environmental Sustainability

Few products actually benefit the environment by being manufactured, and thus the mentality often taken when designing for environmental sustainability is one of a reduction in environmental harm (Diegel et al., 2010). In order to adequately understand the environmental impacts of a project, one must consider its entire life-cycle. An environmentally sustainable product is one that minimizes its effect on the environment over its lifetime. Ideally, products should be designed that are able to reduce fossil fuel use, reduce the use of toxics, minimize the amount of harmful emissions, and promote recycling and reuse when compared to similar alternative products (United Nations Environment Programme, 2009). Melles (2011) states that ”consumers, producers, and designers are being called on to consider the responsibilities of their decisions in relation to design objects in a world of diminishing resources and climate change” (Melles et al., 2011).

Many companies in the developed world find the motivation for being environmentally sustainable as a means of promoting their brand (Fiksel et al., 1998); however, based on the observations of the author, this is really only a concern among the socioeconomic elite of the developing world. Few people among the poor and rural have sufficient education to see the benefits of “green products”. Thus, it has been argued by some that “market environmentalism”, or finding ways to make it economically beneficially to embrace environmentally sustainable practices, is key to encouraging public participation in environmentally friendly consumption (Melles et al., 2015). Factors that contribute to economically sustainable products can also be factors that promote environmentally sustainability. For example, lean supply chains can often result in “green” supply chains, as there is less associated waste (Nyman and Sarlin, 2014).

4.3.2 Considerations for Evaluating a Product’s Environmental Sustainability

The first consideration to be made regarding the environmental sustainability of a product is its energy requirements.

Environmental Sustainability Question 1: How does producing this product with 3D printing reduce total non-renewable energy requirements needed to manufacture it?

All energy requirements for FDM printers, from computer operation to the heating of filament, are dependent on electrical input. As electricity can be generated through a variety of means, the non-renewable energy used to produce a product is difficult to predict as it is dependent on the printer’s source of electricity. However, regardless of the source of electricity, it is advantageous to reduce the amount of energy associated with a product’s manufacture. The environmental impacts of a 3D printer’s energy use could be taken into account with life-cycle analysis [e.g., Kreiger and Pearce (2013), Kreiger et al. (2014), or Faludi et al. (2015)].

Much like the breakeven cost analysis in regards to economic sustainability, small quantities of a product require less energy per product to manufacture using 3D printing. Eventually, however, with large enough quantities, other manufacturing methods become more energy efficient (Campbell et al., 2013). The amount of energy used in 3D printing is directly related to the amount of time used to manufacture the product and therefore related to the total volume of filament used on the product (Faludi et al., 2015). The energy use for a single product's manufacture can be calculated using Equation 6 and Equation 7 found in the viability section.

Energy costs sometimes appear to be smaller when 3D printing with FDM processes then they actually are, because some studies do not account for variations in power usage throughout the manufacturing process, including warm up and idle times (Huang et al., 2013). In fact, the warm up phase before FDM begins is often the most power consuming part of the process (Yoon et al., 2014). The amount of energy required by 3D printers varies greatly by printer, varying by as much as a factor of 6 for the manufacturing of the same object (Walls et al., 2013).

Environmental Sustainability Question 2: Is this product able to reduce the total amount of solid waste in the environment?

Material waste can also be minimized by increasing the longevity of a product's life-cycle. Therefore the more desirable that a product is, the longer the product will survive and the less impact it will leave on the environment (Kreiger and Pearce, 2013).

The consumerist throw-it-away mentality that exists in both the developed world and developing world is detrimental for environmental sustainability (Diegel et al., 2010). It is assumed that 3D-printed objects give more freedom to designers so that they are better able to design for desirability, and therefore longevity, with their products. By reducing manufacturing constraints and allowing for increased complexity and customization, designers are able to pursue products that look better, function better, and consequently may have longer life-cycles and smaller environmental impacts (Kreiger and Pearce, 2013; Diegel et al., 2010).

Plastic products typically have a limited lifespan in the harsher conditions of rural Tanzania. After several years, many houseware items break, become unusable and become more plastic waste that is added to the landscape. While some recycling naturally occurs (Okot-Okumu, 2012), such as the reusing of resealable plastic bottles for the purpose of selling kerosene or local processed kitchen oils, most plastics end up being discarded or burned.

Solid waste accumulation is a major problem throughout the developing world, and East Africa is no exception. There is little formal infrastructure for recycling throughout the Sub-Saharan Africa (United Nations Economic Commission for Africa, 2012; Okot-Okumu, 2012), and there is none whatsoever in rural Tanzania. While statistics for rural areas do not exist, statistics for several urban areas in Tanzania indicate that as much as 9% of solid waste is comprised of plastics (Okot-Okumu, 2012).

There has been considerable work done in regards to developing and assessing the ability to recycle used plastics into filaments for 3D printing. The ability to privatize recycling of plastic waste provides potential for offsetting tremendous amounts of waste in the environment. As filament is produced, waste plastics are removed from the environment. This is not without costs, however, as recycling does require water and electrical energy to process these plastics before filament can be created (Feeley et al., 2014). Water shortages and inconsistent electrical power are often challenges in the developing world that cannot be overlooked.

Environmental Sustainability Question 3: Can this product be manufactured with PLA?

Though they are recyclable, HDPE and ABS are both manufactured from fossil fuels (Franklin Associates, 2011), and thus cannot be considered to be renewable. PLA however, is manufactured from lactic acid, typically derived from corn, and thus is renewable and biodegradable (Hamod, 2015). When possible to satisfy product functionality, it is ideal to use PLA in place of petroleum-based filaments.

Environmental Sustainability Question 4: How much waste associated with packaging can be reduced by manufacturing this product locally?

Distributed manufacturing also presents the ability to reduce the need for excessive amounts of packaging, as products are made closer to its end point of use. Thus, a major form of waste is able to be removed (United Nations Environment Program, 2009). While non-recycled filament would still require shipping, and therefore some degree of packaging, its compactness would likely reduce overall shipping needs (Tatham et al., 2014).

Environmental Sustainability Question 5: How much waste byproduct can be reduced by 3D printing an object versus other forms of manufacturing?

While 3D printing is able to cut back on the material waste associated with a product, the other byproducts of manufacturing must also be considered. There are no cutting fluids associated with 3D printing using FDM, and cutting fluids are often some of the most hazardous byproducts associated with other manufacturing processes (Huang et al., 2013). Some sources claim that there are no harmful byproducts associated with 3D printing at all (Gebler et al., 2014), though this is disputed. A previously noted health concern comes from a study conducted at the Illinois Institute of Technology. This study noted that heated ABS and PLA can give off small amounts ultrafine particles as the plastics go through thermal decomposition, with ABS emitting at a rate 10 times greater than PLA (Stephens et al., 2013). Even more, while the products of heated PLA are largely innocuous and sometimes even used in drug delivery (Anderson and Shive, 2012), ABS was shown to give of carbon monoxide and hydrogen cyanide (Rutkowski and Levin, 1986).

Environmental Sustainability Question 6: How much is fossil fuel consumption reduced by reducing transportation through distributed 3D printing?

Because local manufacturing is able to reduce the need for shipping products long distances from their place of manufacture to their place of sale, it is possible to reduce the transportation fuel costs associated with getting a product to a consumer.

Environmental Sustainability Question 7: How much are greenhouse gas emissions reduced by reducing transportation through distributed 3D printing?

While manufacturing is able to occur on site, this does not automatically mean that there are no associated transportation emissions. The filament, if not produced locally, still needs to be transported from its place of manufacture to the site of printing. If the filament were manufactured on site and out of recycled materials, the transportation emissions could be removed almost entirely.

4.4 Summarizing Questions Related to Sustainability

Much like when evaluating desirability, it is difficult to quantify the metrics of success associated with social sustainability. However, the following questions in Table 17 should be asked of a product that could be 3D printed.

Table 17. Summarizing questions to consider in regards to social sustainability

Question		**Measurement**
1.	What are the total chemical hazards involved in the manufacturing of this product?	Type and number/cm^3
2.	How many of the Sustainable Development Goals are demonstrably able to promote by printing this product?	Number of goals
3.	Does this product require technical knowledge to be able to produce?	Yes/No
4.	Does producing this product by 3D printing reduce wasted human capital?	Yes/No
5.	What are the total amount of man-hours of labor gained by the end user in producing this product locally?	man-hours

In regards to determining the economic sustainability of a 3D printed product, several criteria can be taken from previous discussions. An accurate assessment of the economic sustainability of a 3D-printed product should include an assessment of its business model. Some of these metrics seen in Table 18 are more difficult to quantify than others, but all would be valuable in assessing economic sustainability.

Table 18. Summarizing questions to consider in regards to economic sustainability

Question		**Measurement**
1	How many units of this product must be made before it is more cost effective to manufacture through other techniques?	Number of Product
2	Does manufacturing this product with 3D printing employ additional or improved work opportunities for people within the community?	Number of jobs
3	How much material waste is reduced by manufacturing this product with 3D printing?	kg
4	How much can transportations costs be reduced by manufacturing this product locally?	USD

Just as it is important to assess an entire business model when evaluating a product's economic sustainability, it would also be vital to perform an entire life-cycle analysis when looking at a product's environmental impacts and sustainability. Questions important to consider regarding environmental sustainability can be seen in Table 19.

Table 19. Summarizing questions to consider in regards to environmental sustainability

	Question	**Measurement**
1	How much does producing this product through 3D printing reduce total non-renewable energy requirements needed to produce it?	kwh
2	Is this product able to reduce the total amount of solid waste in the environment?	kg
3	Can this product be manufactured with PLA?	Yes/no
4	How much waste associated with packaging can be reduced by manufacturing this product locally?	kg
5	How much waste byproduct can be reduced by 3D printing an object versus other forms of manufacturing?	kg
6	How much is fossil fuel consumption able to be reduced by reducing transportation through distributed 3D printing?	kg
7	How much are greenhouse gas emissions able to be reduced by reducing transportation through distributed 3D printing?	kg

5.0 Case Study

Now that suitable criteria have been outlined for the evaluation of 3D printing of a product, a case study will be examined. The case will be a product that was necessary for projects during the author's Peace Corps service and could have been potentially manufactured locally through 3D printing.

5.1 Laboratory Supplies

Education is a critical need in Sub-Saharan Africa and throughout the developing world, as reflected in the Sustainable Development Goals. Increased technical capability is vital, and scientific and engineering education is recognized as a critical component for Sub-Saharan African Development (Sustainable Knowledge Platform, 2015). A large part of the author's Peace Corps service was dedicated to the development of science materials and curriculum through the Shika Kwa Mikono ('Grasp with the Hands' in Swahili) program, supported by Peace Corps Tanzania and the Tanzanian Ministry of Education.

Each year in Tanzania, all graduating secondary school students are required to take national examinations that include a hands-on, practical portion. These practical exams in physics, chemistry, and biology require different equipment and materials to be procured and prepared by teachers. As evidenced in Figure 16, limited budgets and remote locations often make this difficult, and oftentimes insufficient access to laboratory equipment impedes the ability of students to develop and demonstrate the skills necessary to meet the requirements of these examinations and further their education.

Figure 16. Science laboratory of Ismani Secondary School (photo by author)

A common piece of laboratory equipment needed for these exams is a set of Vernier calipers, like those seen in Figure 17 below. Physics students are required to make measurements with calipers for their examinations, though there are few opportunities to be able to use them. At Ismani Secondary School, there were only two sets of calipers available for over 700 students. Practicing the necessary skills was therefore nearly impossible.

Figure 17. Vernier Calipers with packaging available for sale in Tanzanian town
(Photos by Caitlin Baumhart)

If a localized 3D printer were operating in Ismani, it is possible that calipers could be manufactured to provide additional student access to the product. Thus, the human-centered design and sustainability criteria outlined in sections 3 and 4 will be used, and it will be evaluated whether or not Vernier calipers would be appropriate to manufacture using 3D printing. In this scenario, calipers would be produced for students at Ismani Secondary School. As the number of students enrolled in fourth year physics classes is typically 50 at Ismani Secondary School, and there are 30-40 students total from the other two schools of the Ismani area, it will be assumed that 80-100 sets of calipers will be produced for the laboratories. The printer will be a RepRap Prusa Mendel, as it is the open source printer with the most available data. Finally, it will be assumed that manufacturing will take place in Ismani village, as Ismani is already equipped with electrical connectivity and is one of the few villages the school serves that currently has this capability. Virgin ABS filament is going to be used in this example.

5.1.1 Evaluation of Vernier Calipers for 3D printing Using Human-centered Design Criteria

First the calipers must be evaluated in terms of desirability, feasibility, and viability for production using 3D printing.

Desirability Question 1: Has the desirability of this product already been demonstrated through a comparable product in the market?

Yes, the calipers are already available for purchase in most large Tanzanian towns. Though the demand may not be exceptionally high, demand does exist as schools are forced to have laboratory equipment for their practical examinations. There are three secondary schools in the Ismani area, and all would need to be able to administer exams at the same time. The author estimates that this would include 80-100 students needing to use calipers over the course of the examination period.

Desirability Question 2: Will the perceived benefits of an existing product be increased by manufacturing it through 3D printing?

As mentioned, it is difficult to quantify the perceived values of a product is, but it is possible that 3D-printed plastic calipers would be perceived as less valuable than traditional metal calipers. This is because plastics are generally less durable than metals, and, as noted, durability is generally associated with quality to BOP consumers (Whitehead et al., 2014).

Though it can already be seen that a small market space exists for the product, it is still beneficial to determine what benefits the product will bring to consumers.

Functional benefits

Both the 3D printed calipers and traditionally manufactured ones are able to provide functional benefits to students, the end users, by enabling them to make measurements and practice and perform practical exams. Both will be given a benefit rating of 3.

Social Benefits

It is unlikely that there would be significant social status benefits accompanied by using the calipers. Both the 3D-printed and metallic calipers will be given a benefit rating of 0.

Emotional Benefits

There are few sentimental emotional benefits associated with the usage of calipers other than perhaps benefits that could be derived from accomplishment of a successful practical exam. Both versions of the calipers will be given a rating of 1.

Epistemic Benefits

The educational improvement and skill development of having calipers available will also bring the epistemic benefits to the user. As the calipers are to be used for educational purposes, both will be given a benefit rating of 2.

Aesthetic Benefits

The calipers would not be directly associated with any aesthetic benefits. However, 3D-printed calipers could be customized by color or labels. Thus the 3D-printed calipers will be given a benefit rating of 1 while the purchased calipers 0.

Hedonic Benefits

The calipers have no value directly associated with enjoyment. The 3D printed and purchased calipers will both be given a rating of 0.

Situational Benefits

The product could be used to fulfill specific needs during the national examinations by meeting the requirements of the national examination council. Both products would be able to cater to the situational demand surrounding their use and will thus be given a benefit rating of 2.

Holistic Benefits

The end users will experience a degree of accomplishment made possible by exercising the skills associated with using the calipers. This is not, the intended function of this product, however, and thus both products will be given a rating of 2.

Thus, by assigning values to all of the benefit types according to the definitions of Table 2 totals can be compiled, as see in Table 20.

Table 20. Summary of benefit ratings for printed and purchased calipers

Benefit Type	3D-printed calipers	Purchased Calipers
Functional	3	3
Social	0	0
Emotional	1	1
Epistemic	2	2
Aesthetic	1	0
Hedonic	0	0
Situational	2	2
Holistic	2	2
Total	**11**	**10**

By using the data in Table 20 and Equation, a benefit ratio of 1.1 can be calculated. Because this value is relatively close to 1.0, it cannot be definitively stated whether or not a 3D-printed version of a part can supply more benefits to users than the purchased calipers.

To assess the feasibility and viability of producing the calipers, it is necessary to start looking at a specific CAD design. Several designs for calipers exist on the open source website “Thingiverse”, and one was chose that uses metric units (RubeGolberg, 2013).

Feasibility Question 1: Does this part have complex geometry that could not be achieved with other manufacturing methods?

By examining the CAD file seen in Figure 18, it is evident that the part is made from relatively few geometric shapes and would probably not benefit from 3D printing. Most of its complexity comes from its millimeter demarcations.

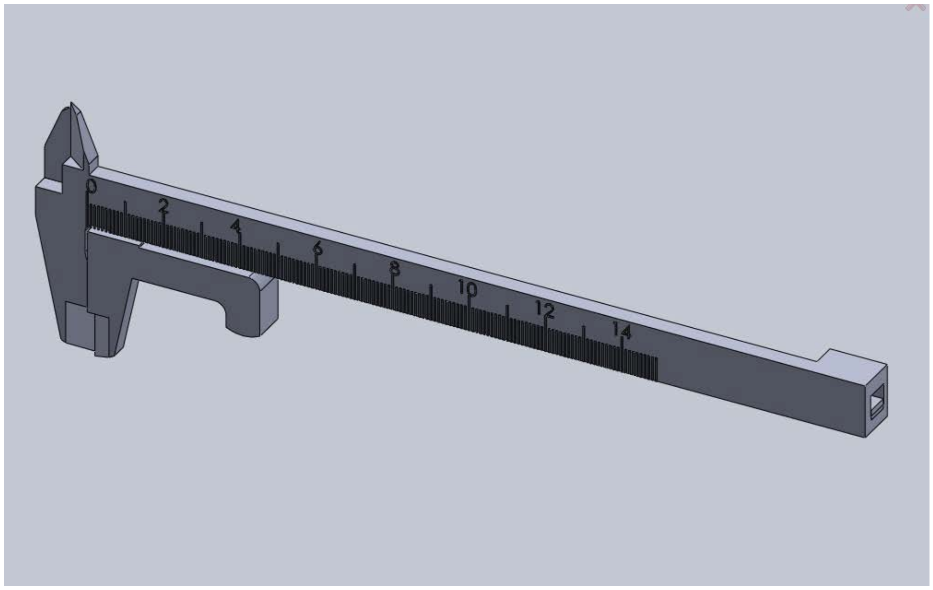


Figure 18. CAD model of Vernier calipers (RubeGolberg, 2013)

The calipers could be made with other manufacturing methods, and thus 3D printing offers no clear advantage in this regard.

Feasibility Question 2: What is the build envelope of the product?

The calipers are comprised of two parts with build envelopes of 217mm x 65.05mm x 11.20 mm and 217.21mm x 65.05mm x 9.00mm (RubeGolberg, 2013). As the build envelope of the Prusa Mendel is 200 mm x 200mm x 110mm (Pirjan and Petrosanu, 2013) the calipers can be manufactured using the printer, but it may require one part to be manufactured at a time depending on the slicing software used.

Feasibility Question 3: What level of customizability is required?

Generally, no customization is associated with calipers, thus according to the scale outlined by Conner et al. (2014) and seen in Table 3, the calipers would be given a customizability rating of 0. However, if students owned their own sets, as they often do with rulers, they would be able to personalize them by color, possibly making them more desirable and giving it a customization rating of 1. In either case, it would not be advantageous to produce calipers with 3D printing because of customizability.

Feasibility Question 4: Does the product's function benefit from having a specified density?

No, the product's function is not dependent on its density. 3D printing offers no advantage in this regard.

Feasibility Question 5: What is the maximum temperatures to which this product will be exposed?

The physics laboratory practice sessions and practical exams will be conducted at room temperature, which is significantly less than the 100°C that ABS reaches its glass transition temperature (Hamod, 2105). Temperature should not be a concern.

Feasibility Question 6: What is the maximum stress due to tension this product will experience?

None, there should not be any significant tension forces applied to this product during its intended use.

Feasibility Question 7: What is the maximum stress due to compression this product will experience?

None, there should not be any significant compression forces applied to this product during its intended use.

Feasibility Question 8: What is the maximum stress due to flex this product will experience?

None, there should be not be any significant flexural forces applied to this product during its intended use.

Feasibility Question 9: What is the maximum impact this product will experience?

None, there should be not be any significant impact forces applied to this product during its use.

Feasibility Question 10: What is the ultimate stress associated with fatigue this product will experience?

None, fatigue should not be a significant concern with this product.

As calipers are used as a measuring device, they are generally do not experience significant stresses during their intended use. It should be noted, however, there are no guarantees that students will not abuse calipers, and therefore some consideration should still be given to the general durability of plastic calipers versus metal ones. Still, Feasibility Questions 6-10 will not be considered significant concerns.

Feasibility Question 11: What is this product's ability to resist wear?

As mentioned, the forces a set of calipers are subjected to are generally minimal, and concerns regarding sliding wear are probably also minimal. However, as Vernier calipers are comprised of two parts that are manufactured to slide against one another, this could become a concern with exceptionally rough surfaces. These forces would have to be quantified and compared to the data shown earlier in this report. In this regard, if friction becomes a concern, the calipers may need to be subjected to chemical treatment to reduce surface roughness.

Feasibility Question 12: What resolutions are required of this part?

The calipers will be used for measurement, and for the practical exams may require accuracy to a tenth of a millimeter. When comparing this requirement to the data in Table 9 from Section 3, it can be seen that a well calibrated Prusa Mendel could, theoretically, attain sufficient resolution for printing demarcations at the tenth of a millimeter, but not with distinct incremental marks. This level of accuracy is at the limit of the printer's technology and, realistically, even the most accurate prints still have error and deviate from the CAD drawings (Lanzotti et al., 2015). It should also be noted that currently the CAD file does not include demarcations for tenths of a millimeter, though with sufficient knowledge of software, this could be modified.

Feasibility Question 13: Does the part require a water tight seal?

No, this is not a concern for the calipers.

Viability Question 1: How much does the product cost to make?

In order to calculate the total cost of the parts, Equation 3 will be used.

$$C_{part} = C_{pre} + E_{total} * C_E + m_f * C_f + C_{post} \qquad \text{Equation 3}$$

While the CAD file is already available, there are no preprocessing costs associated with manufacturing this product. Similarly, there are no apparent post-processing costs, unless it is determined that the part will need chemical treatment. The mass of the part can be estimated using the open source slicing software Cura. The mass of the part is estimated to be 33 grams, and 18 grams if infill is reduced to 10%. The cost of filament will be assumed to be 35 USD/kg, and the power usage of the Prusa Mendel to be 60W, based on similar variables used in experiments by Wittbrodt (Wittbrodt et al., 2013) and Walls (Walls et al., 2014), respectively. The slicing software is also able to estimate time. Cura estimates that the calipers will take 130 minutes to manufacture, or 67 minutes if the infill is reduced to 10%. Using these variables and a power cost of 0.032 USD/kWh (TANESCO, 2015a), the total cost of the calipers can be calculated to be 1.16 USD or 0.63 USD for 10% infill.

Viability Question 2: What are people able to pay for this product?

Iringa town is the nearest place to Ismani where one can procure a set of Vernier calipers. The price is approximately 15000 Tanzanian shillings, or approximately 8.12 USD. This product is able to be sold at this price, but it should be noted that this price is to some degree prohibitive, as few Tanzanian schools invest in many sets.

While it is tempting to presume that the difference between the current price of calipers and the cost of making calipers with 3D printing could be the potential profit margin, this is not accurate. As mentioned, the perceived value of plastic calipers would most likely be less than metal ones. However, they could be the preferred option over metal calipers by differentiating themselves through lower costs. The amount that consumers would be willing to pay would probably be substantially less than the price of metal calipers, but significant profit could still be made. More extensive market research would be necessary to know accurately, but it is reasonable to believe that the calipers could be sold for 3000 Tanzanian shillings, or 1.61 USD. If so, and it were assumed that no additional costs were incurred because of the local manufacturing and greatly simplified supply chain, the profit margin per set of calipers could be 0.45 USD.

Viability Question 3: How much time does it take to produce the product?

Again referring to the estimations made by Cura, the total time needed to produce this product is approximately 130 minutes (or 67 minutes if infill is reduced to 10%). Pre-processing and post processing costs would probably be minimal, as the part requires no modification before printing and as there are few overhanging edges or concave faces that would require supports. Post processing with ABS may be necessary along the sliding surfaces of the caliper. Over the course of a work day, 4 to 12 calipers could potentially be produced.

Viability Question 4: What are the energy demands and energy cost of producing this product?

Assuming that the printer used is a RepRap Prusa Mendel, the energy costs should be approximately 0.12 kWh (or 0.05 kWh if infill is reduced to 10%). This should be affordable to many Tanzanian entrepreneurs as average energy costs in rural Tanzania are 0.032 USD/kWh (TANESCO, 2015a). The energy cost to produce the part using 3D printing is less than 0.01 USD.

Social Sustainability Question 1: What are the total chemical hazards involved in the manufacturing of this product?

In order to reduce the friction on the sliding parts of the calipers, the ABS parts should be treated with acetone to remove surface roughness. While not as dangerous as other chemicals, it is still important to note that any potential chemical hazard should be considered a chemical hazard.

The total concentration of fumes that an individual would be exposed to would depend on a variety of factors including the airflow around the printer, but this hazard could be quantified using methodology similar to that outlined by Stephens et al. (2013). Because ABS gives off some harmful fumes, such emissions should be taken into account.

Social Sustainability Question 2: How many of the Sustainable Development Goals are promoted by printing this product?

Goal 4 of the Sustainable Development Goals is concerned with increased access to education and educational activities, particularly activities involving science and technical skills (Sustainable Development, 2015). The use of this product falls right in line with this Sustainable Development Goal.

Social Sustainability Question 3: Does this product require special technical knowledge to be able to produce?

Yes, this design would require modifications to print as the CAD file lacks demarcations for reading to the tenth of a millimeter, and thus it would require some basic CAD skills to modify. Even if these changes were made on the CAD drawing, they may not be achievable by the printer due to resolution limits.

Social Sustainability Question 4: Does producing this product by 3D printing reduce wasted human capital?

There is little need for creative inputs to this product, and thus this product is not really a springboard for innovation. However, the reduced cost of producing this product through 3D printing enables more educational opportunities and enables more students to have academic success.

It is unlikely that with the limited number of calipers to be sold that the production of this product on its own could be sufficient to start a new business. Thus entrepreneurial opportunities this product would provide would probably be minimal.

Social Sustainability Question 5: What are the total amount of man-hours of labor gained by the end user by producing this product locally?

It is a 1.5 hour bus ride to Iringa town from Ismani. In most cases, if some supplies are needed to be procured for Ismani Secondary School, a teacher would be sent as a representative to make the purchases. If such a representative from the school were to go to Iringa town with the purpose of procuring Vernier calipers, there would be at least 3 hours of wasted man-hours that could be used for teaching or other education activities.

Economic Sustainability Question 1: How many units of this product must be made before it is more cost effective to manufacture through other techniques?

The breakeven point for manufacturing this specific part can be compared to using ABS through injection molding. By utilizing a cost estimation model from Massachusetts Institute of Technology (MIT) for injection molded parts, it can be estimated that, disregarding initial machinery investments, over 20,000 sets of ABS calipers would need to be produced before each part would be able to match the total cost of 0.87 USD per caliper using the 3D printer in this scenario. This can be seen in Figure 19. As the projected demand for Ismani would be 80-100 calipers, it would not be effective to manufacture these locally using injection molding.

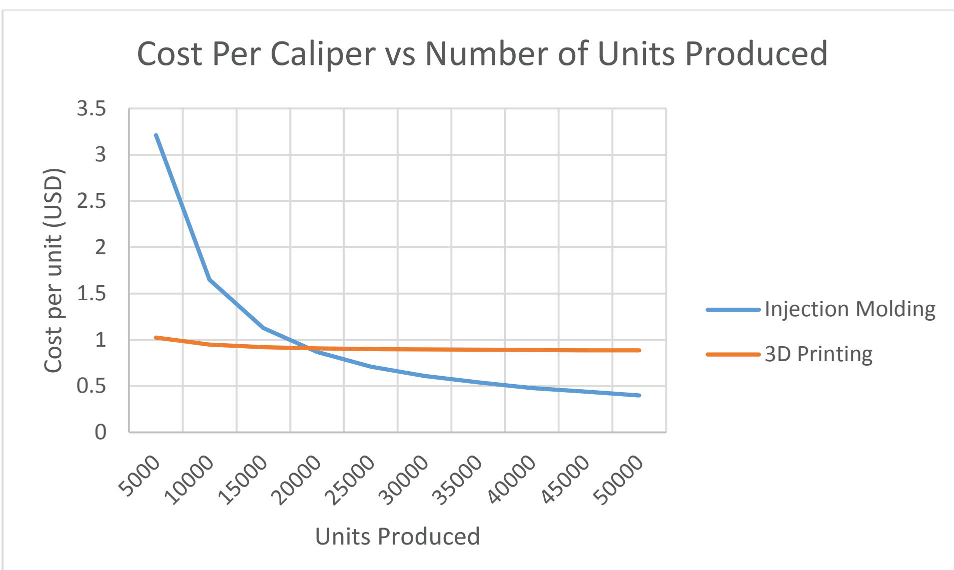


Figure 19. Comparison of manufacturing plastic calipers with 3D printing and injection molding

It should be noted that the amount of time required to manufacture the calipers is significantly higher for 3D printing. As noted in Viability Question 3, it would take 67-130 minutes to manufacture a set of calipers, not including pre- or post-processing time. Most other manufacturing methods, but especially injection molding, would be able to manufacture calipers on a much smaller time scale.

Economic Sustainability Question 2: Does manufacturing this product with 3D printing employ additional or improved work opportunities for people within the community?

It is unlikely that the printing of Vernier calipers would be directly responsible for the creation of new jobs. As the calipers are being manufactured with virgin ABS in this scenario, removal of plastics to be recycled would not be necessary for production.

Economic Sustainability Question 3: How much material waste is reduced by manufacturing this product with 3D printing?

There is little direct reduction in material waste by producing this product through 3D printing; however, the reduction in infill could potentially result in a material savings of 15g of ABS. A more thorough analysis of alternative manufacturing methods would be need to be accurately undertaken in order to better estimate the advantage 3D printing could afford.

Economic Sustainability Question 4: How much can transportations costs be reduced by manufacturing this product locally?

As mentioned, procuring calipers in town currently involves transportation to and from Iringa town, which would be a total journey costing 6000 Tanzanian Shillings (3.20 USD). However, there would generally be no other additional costs with transporting the calipers back to town. The total cost of transporting the filament to Ismani from town would also be 6000 Tanzanian shillings, however, this cost could be distributed across the total uses of the filament as only a small fraction of a total filament spool would be used to print calipers.

Environmental Sustainability Questions 1: How much does producing this product with 3D printing reduce total non-renewable energy requirements needed to produce it?

A full life-cycle analysis for the Vernier calipers purchased in town would be required to evaluate the energy used in producing them. However, it is likely that it would still be higher than the 0.125 kWh used in printing the 3D calipers.

In July of 2014, the conclusion of the author's Peace Corps service, Ismani was connected to the Tanzanian Electric Supply Company (TANSECO) electrical grid. The exact source of the electricity used in Ismani is not known, but it is most likely generated by nearby Mtera Dam. TANESCO states that 90% of the electricity that it produces is from hydroelectric sources (TANESCO, 2015b) and Mtera Dam is understood by most people to be the primary power source for the northern part of the Iringa region. Thus, it is likely that the non-renewable resources consumed during manufacturing are probably minimal. However, it should be noted that hydroelectric power is not without other environmental effects.

Environmental Sustainability Question 2: Is this product able to reduce the total amount of solid waste in the environment?

While ABS is recyclable, it is not as plentiful or as easily recyclable as HDPE or other plastics. If the filament used to produce the product was made from completely recycled filament, 18-33 grams of waste ABS would be removed from the environment per set of calipers made.

Environmental Sustainability Question 3: Can this product be manufactured with PLA?

This product will be made with ABS as it appears to meet all necessary material requirements. There is no mechanical requirement that would prevent the calipers from being made with PLA, however, and this design change should be considered since PLA is more environmentally friendly.

Environmental Sustainability Question 4: How much waste associated with packaging can be reduced by manufacturing this product locally?

As seen in Figure 17 above, the calipers currently available in Iringa town are shipped within a cardboard sleeve of estimated 25g and polyethylene packaging of 5g. This can be compared to the approximately 100g cardboard spool associated with the filament; however, only 24g of the kilogram of filament (or 2.4% of an 1kg spool) would be used for one set of calipers, so the actual packaging waste per set of calipers could be reduced from 25g of cardboard and 5 of polypropylene to just 2.4 grams of cardboard.

Environmental Sustainability Question 5: How much waste byproduct can be reduced by 3D printing an object versus other forms of manufacturing?

The exact manufacturing method of the Vernier calipers that are sold in Iringa town needs to be better understood before an accurate comparison can be made. A full life-cycle analysis of the product of the calipers would need to be undertaken to better quantify the total waste in manufacturing the product.

Environmental Sustainability Questions 6 and 7: How much is fossil fuel consumption able to be reduced by reducing transportation through distributed 3D printing? How much are greenhouse gas emissions able to be reduced by reducing transportation through distributed 3D printing

These questions require a full life-cycle analysis in order to be able to quantify the reductions in greenhouse gas emissions and fossil fuel consumption. However, even by examining the portion of the life-cycle that involves transportation from Iringa town, a total of 45 kilometers are traversed by public bus when procuring either a set of calipers or the necessary filament. However, each set of 3D-printed calipers only accounts for 2.4% of the total spool of filament, and thus only 2.4% of the total fuel use and 2.4% of the emissions.

5.1.2 Summary of Criteria Regarding Assessment of Production of 3D-printed Vernier Calipers

While calipers are not highly desirable products and 3D printing can add little to their desirability, they are made necessary by their requirements in education and examinations. With respect to feasibility, the calipers have relatively low expected stresses, and so using the thermoplastics associated with the process, specifically ABS, should be sufficient. The only possible mechanical failure to occur under appropriate use would be slide wear, though this is unlikely and could be improved with chemical treatment. The accuracy required, however, may be a larger concern as the resolution and precision of low cost 3D printers are currently insufficient to produce calipers able to measure to the tenth of a millimeter with confidence.

Producing the calipers with 3D printing can indeed be considered viable as they can be manufactured for as little as 0.34 USD each. The perceived values will probably be substantially less than the metal calipers commonly available, but the ability to strongly undercut prices could prove critical to gaining a viable product.

Social sustainability is largely not a concern. Wasted man-hours can be reduced by local production and eliminating the need for travel. As the calipers are an educational product, the use of the product aligns with Sustainable Development Goals. There are few immediate benefits to economic sustainability from 3D printing of calipers, as relatively few items would need to be made. The total environmental impacts would require a full LCA to adequately quantify, though it appears to be environmentally beneficial to print rather than purchase calipers.

While the calipers would be a possible candidate for localized 3D printing production, it is not recommended that they are produced. Even if the cost per caliper is significantly reduced, the calipers' primary benefit is the ability to make accurate measurements, and the accuracy of the calipers is limited by the resolution of the printer. Ideally, a higher quality printer could be used to achieve more accurate parts and make 3D manufacturing of calipers feasible.

It should be noted that, if the primary function of the calipers is to allow the students to practice measurements, the low resolutions achievable by less expensive printed calipers could still be used during instruction. This would depend upon the teacher ensuring that the procedure the students are using is correct and that more accurate calipers could be attained for the actual examinations.

6.0 Conclusions

As the four billion consumers at the Bottom of the Pyramid continue to desire both increased access to consumer goods and increased participation in global economies, it becomes increasingly important for designers and manufacturers to consider how this desire will be met. This trend will provide a major challenge and opportunity for the people in developing countries and people who are involved with those countries' development. 3D printing presents a manufacturing option that has the potential to allow many from the BOP to be able to actively participate in the growth of their local economies and manufacture goods where and when they are demanded.

The purpose of this paper is to determine criteria that could be used to preemptively evaluate a product's suitability for manufacturing through 3D printing. Two sets of design criteria were applied along with specific considerations that would be relevant for 3D printing in Sub-Saharan Africa, specifically Tanzania. The first set of criteria was the human-centered design criteria from the design firm IDEO. Key questions concerning a product's customer desirability, technical feasibility, and financial viability, were discussed and defined. The second set of criteria utilized were those of sustainable development. From this, questions were defined in regards to assessing the social, economic, and environmental sustainability of products potentially manufactured with 3D printing. The human-centered design and sustainability questions were then put into practice by examining a case study of producing a set of Vernier calipers for use in a school laboratory in rural Tanzania.

These criteria are important as they will help in the decision making process as companies and individuals evaluate how 3D printing can fit into BOP markets. By merging human-centered design criteria with considerations of sustainability, it is possible to examine the specifics of 3D printing and how it would be implemented in the developing world. Much study and discussion has been conducted concerning the larger position that 3D printing may occupy in a developing world economy, but many of the opportunities and challenges of on-the-ground implementation have yet to be seriously considered. This paper begins to address those considerations by developing a framework for the evaluation of the products that 3D printing could produce. This evaluation finds 3D printing to be flexible and able to affect how a variety of products are manufactured, but indicates there are still many limitations on what can be produced with the technology as it currently exists. These limitations are largely imposed by the consistency, precision, and strength achievable by the fused deposition modeling process. Additionally, as most FDM processes rely on the use of thermoplastics, the range of materials that can be used to cost effectively print 3D-parts needs to be expanded to allow for more durable and varied parts demanded by BOP markets. Because of these limitations, the products which can be effectively printed are still limited. However, as the technology further develops and design for FDM or other 3D printing processes is improved, the quality and variety of desirable, feasible, and viable parts that are printed will increase.

There still may be, however, a space in developing world markets for this technology and its products. Products that require a high degree of customization, parts that have low strength requirements, and products that are manufactured in small batches will be some of the first products that benefit from 3D printing. In Tanzania this could include certain specialty educational and medical equipment or various decorative artifacts that are sold throughout the country's markets. However, even the success of these offerings will depend upon improved capabilities of the printers being used and the education and operational abilities of the people using the printers in Tanzania.

These questions for evaluating 3D printed products can be used by designers, manufacturers, entrepreneurs, and other developing world actors to contribute to the ongoing discussion that is shaping the 3D printing ecosystem as it moves closer to its potential application. The sustainability considerations listed will be critical in evaluating the greater impact products have in Tanzania and in the lives of BOP consumers everywhere. Additionally, as relatively limited research has been done concerning developing world consumers, the framework used in this paper could be adapted and used for future analysis of products and manufacturing technologies for the countries and cultures throughout the developing world.

These questions are not complete and will continually need refining as they are applied in different economic and cultural settings. In the future, this work would benefit from more case studies in order to better understand and develop the design and decision making processes. Also, the ability to better quantify many of these metrics and integrate a full life-cycle analysis of products would make decision making processes more objective and verifiable. Aspects regarding social sustainability, and desirability in particular, would greatly benefit from increased market research and understanding of BOP countries like Tanzania. Concerns regarding technical feasibility would also greatly benefit from more data available on material and mechanical properties of 3D-printed objects. Ideally, a product could be fully understood through finite element analysis methods before production, rather than comparing the product's loads to scattered experimental results. Such concerns should all be reviewed and refined as the applicability of 3D printing for the BOP is further explored in years to come.

References

3D Printing from Scratch. (2015). 3D printer Filament Types Overview. Retrieved from http://3dprintingfromscratch.com/common/3d-printer-filament-types-overview/#hips-pva. Accessed 3/15/2015.

Ahn, S. H., Montero, M., Odell, D., Roundy, S., and Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling. *ABS.Rapid Prototyping Journal*, 8(4), 248-257.

Alexander, P., Allen, S., and Dutta, D. (1998). Part orientation and build cost determination in layered manufacturing. *Computer-Aided Design*, 30(5), 343-356.

Anderson, J. M., and Shive, M. S. (2012). Biodegradation and biocompatibility of PLA and PLGA microspheres. *Advanced Drug Delivery Reviews*, 64, 72-82.

Arumaikkannu, G., Uma Maheshwara, N., and Gowri, S. (2005). A genetic algorithm with design of experiments approach to predict the optimal process parameters for FDM. *Solid Freeform Fabrication Symposium*. Austin, TX.: University of Texas at Austin.

Baechler, C., DeVuono, M., and Pearce, J. M. (2013). Distributed recycling of waste polymer into RepRap feedstock. *Rapid Prototyping Journal*, 19(2), 118-125.

Banerjee, A. V., and Duflo, E. (2007). *The economic lives of the poor. The Journal of Economic Perspectives: a Journal of the American Economic Association*, 21(1), 141.

Batra, R., Ramaswamy, V., Alden, D. L., Steenkamp, J. B. E., and Ramachander, S. (2014). Effects of brand local and non-local origin on consumer attitudes in developing countries. *Journal of Consumer Psychology*, 9, 83-95.

Berman, B. (2012). 3-D printing: The new industrial revolution. *Business horizons*, 55(2), 155-162.

Beyer, C. (2014). Strategic implications of current trends in additive manufacturing. *Journal of Manufacturing Science and Engineering*, 136(6), 64-70.

Birtchnell, T., and Hoyle, W. (2014). 3D printing for development in the global south: The 3D4D Challenge. Palgrave Macmillian.

Boston Consulting Group. (2009). *The Next Billions: Unleashing Business Potential in Untapped Markets*. World. Retrieved from http://www.weforum.org/pdf/BSSFP/NextBillionsUnleashingBusinessPotentialUntappedMarkets.pdf. Accessed 2/12/2015.

Brown, T. (2009). *Change by Design*. HarperCollins e-books.

Brundtland, G. H. (1987). *Brundtland Report. Our Common Future: Report of the World Comission on Environment and Development*. Oxford University.

Campbell, R. I., Jee, H., and Kim, Y. S. (2013). Adding product value through additive manufacturing. *Proceedings from ICED 13: 19th International Conference on Engineering Design*. Seoul, South Korea.

Campbell, T., Williams, C., Ivanova, O., and Garrett, B. (2011). Could 3D printing change the world? Technologies, Potential, and Implications of Additive Manufacturing. *Atlantic Council*. Washington, DC.

Castillo, L. G., Diehl, I. J. C., and Brezet, J. C. (2012). Design Considerations for Base of the Pyramid (BOP) Projects. *Proceedings from the Cumulus Helsinki 2012 Conference*. Helsinki, Finland.

Chennakesava, P., and Narayan, Y. S. Fused Deposition Modeling-Insights. *Proceedings from ICAD&M'14: International Conference on Advances in Design and Manufacturing*. Tamilnadu, India.

Chin Ang, K., Fai Leong, K., Kai Chua, C., and Chandrasekaran, M. (2006). Investigation of the mechanical properties and porosity relationships in fused deposition modelling-fabricated porous structures. *Rapid Prototyping Journal*, 12 (2), 100-105.

Central Intelligence Agency. (2014). Tanzania in the World Factbook. Retrieved from https://www.cia.gov/library/publications/the-world-factbook/geos/tz.html.

Conn, R. E., Kolstad, J. J., Borzelleca, J. F., Dixler, D. S., Filer, L. J., LaDu, B. N., and Pariza, M. W. (1995). Safety assessment of polylactide (PLA) for use as a food-contact polymer. *Food and Chemical Toxicology*, 33(4), 273-283.

Conner, B. P., Manogharan, G. P., Martof, A. N., Rodomsky, L. M., Rodomsky, C. M., Jordan, D. C., and Limperos, J. W. (2014). Making sense of 3-D printing: Creating a map of additive manufacturing products and services. *Additive Manufacturing*, 1, 64-76.

Day, G. S. (1990). *Marketing Driven Strategy: Process for Creating Value*. New York, Free Press.

Diegel, O., Singamneni, S., Reay, S., and Withell, A. (2010). Tools for sustainable product design: Additive Manufacturing. *Journal of Sustainable Development*, 3(3), 68-75.

Diegel, O., Singamneni, S., Reay, S., and Withell, A. (2013). Sustainable product design through additive manufacturing. *International Journal of Applied Science and Technology*, 4(1), 39-45.

Donaldson, K. (2009). The future of design for development: three questions. *Information Technologies and International Development*, 5(4), 97.

Donaldson, K. M. (2006). Product design in less industrialized economies: constraints and opportunities in Kenya. *Research in Engineering Design*, 17(3), 135-155.

Durgun, I., and Ertan, R. (2014). Experimental investigation of FDM process for improvement of mechanical properties and production cost. *Rapid Prototyping Journal*, 20(3), 228-235.

Edwards, TE. (January 16, 2015). 3D printers in Tanzania with E-Waste, thanks to Finnish Government. Retrieved from http://3dprint.com/37662/3d-printing-in-dar-es-salaam/. Accessed 1/29/2015.

El-Gizawy, A. Sherif, Shan Corl, and Brian Graybill. (2011). "Process induced Properties of FDM Products." *Proceedings from ICMET, International Conference on Mechanical Engineering and Technology Congress and Exposition*. Wembley, England.

Faludi, J., Bayley, C., Bhogal, S., and Iribarne, M. (2015). Comparing Environmental Impacts of Additive Manufacturing vs. Traditional Machining via Life-Cycle Assessment. *Rapid Prototyping Journal*, 21(1).

Feeley, S. R., Wijnen, B., and Pearce, J. M. (2014). Evaluation of Potential Fair Trade Standards for an Ethical 3-D Printing Filament. *Journal of Sustainable Development*, 7(5).

Fiksel, J., McDaniel, J., and Spitzley, D. (1998). Measuring product sustainability. *Journal of Sustainable Product Design*, 7-18.

Fisher Scientific. (2009). Materials Safety Data Sheet: Acetone. Retrieved from http://www.ifa.hawaii.edu/instr-shop/SDS/Acetone.pdf. Accessed 3/20/2015.

Franklin Associates. (2011). Crade-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors: Final Revised Appendices. Plastic Division of the American Chemistry Council. Prairie Village, KS.

Garter, Inc. (2014). Garter Says Consumer 3D Printing is More than Five Years Away [Press Release]. Retrieved from http://www.gartner.com/newsroom/id/2825417. Accessed 2/2/2015.

Gebler, M., Uiterkamp, A. J. S., and Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, 74, 158-167.

Ger, G., Belk, R. W., and Lascu, D. N. (1993). The development of consumer desire in marketizing and developing economies: The cases of Romania and Turkey. *Advances in Consumer Research*, 20(1), 102-107.

Geraedts, J., Doubrovski, E., Verlinden, J., and Stellingwerff, M. (2012). Three views on additive manufacturing: business, research and education. Proceedings from the 9th International Symposium on Tools and Methods of Competitive Engineering. Karlsruhe, Germany.

Gershenfeld, N. (2012). How to make almost anything: The digital fabrication revolution. *Foreign Affairs*, 91, 43.

Górski, F., Wichniarek, R., and Kuczko, W. (2014). Influence of filling type on strength of parts manufactured by Fused Deposition Modelling. *Journal of Machine Engineering*, 14.

Govers, P. C. M., and Mugge, R. (2004). “I love my Jeep, because it's tough like me.”:The effect of product personality congruence on product attachment. Proceedings on the Fourth International Conference on Design and Emotion. Ankara, Turkey.

Gwamuri, J., Wittbrodt, B. T., Anzalone, N. C., and Pearce, J. M. (2014). Reversing the trend of large scale and centralization in manufacturing: The case of distributed manufacturing of customizable 3-D-printable self-adjustable glasses. *Challenges in Sustainability*, 2(1), 30-40.

Hammond, A. (2007). *The next 4 billion: Market size and business strategy at the base of the pyramid*. Washington, DC: World Resources Institute, International Finance.

Hamod, H. (2015). Suitability of recycled HDPE for 3D printing filament. Thesis, Arcada University of Applied Science, Helsinki, Finland. Retrieved from: http://www.theseus.fi/bitstream/handle/10024/86198/Thesis%20final.pdf?sequence=1. Accessed 2/2/2015.

Hatch, G., Becker, P., and van Zyl, M. (2011). The dynamic African consumer market: Exploring growth opportunities in Sub-Saharan Africa. Accenture. Johannesburg: South Africa.

Hattingh, D., Russo, B. Sun-Basorun, A. and Van Wamelen, A. (2012). *The Rise of the African Consumer: A Report from Mckinsey's Africa Consumer Insights Center*. Mckinsey and Company.

Henrique Pereira Mello, C., Calandrin Martins, R., Rosa Parra, B., de Oliveira Pamplona, E., Gomes Salgado, E., and Tavares Seguso, R. (2010). Systematic proposal to calculate price of prototypes manufactured through rapid prototyping an FDM 3D printer in a university lab. *Rapid Prototyping Journal*, 16(6), 411-416.

Hergel, J., and Lefebvre, S. (2014, May). Clean color: Improving multi-filament 3D prints. *Computer Graphics Forum*, 33 (2), 469-478.

Hopkinson, N., Hague, R., and Dickens, P. (Eds.). (2006). *Rapid manufacturing: an industrial revolution for the digital age*. John Wiley and Sons.

United Nations Development Program. (2013). Human Development Index. Retrieved from http://hdr.undp.org/en/content/human-development-index-hdi-table. Accessed 1/29/2015.

Huang, S. H., Liu, P., Mokasdar, A., and Hou, L. (2013). Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology*, 67(5-8), 1191-1203. Chicago.

Human Factors International. (2011). Innovative Solutions for Designing for Emerging Markets: A Conversation with Apala Lahiri Chavan. Fairfield, IA. Human Factors International.

IDEO. (2009). Human Centered Design Toolkit: 2nd Edition.

INEOS. (2009). Data Sheet for Lustran ABS 552 (Extrusion Grade). Retrieved from http://www.allenx.com/uploads/data-sheets/suppliers/ineos552.pdf. Accessed 3/23/2015.

Ishengoma, F. R., and Mtaho, A. B. (2014). 3D Printing: Developing Countries Perspectives. DOI: 10.5120/18249-9329.

Jacobs, D., and Brand, J. (2007). *Adding values: the cultural side of innovation*. Routledge.

Karnani, A. (2007). The Mirage of Marketing to the Bottom of the Pyramid. *California Management Review,* 49(4), 90-111.

Kijazi, A. L., Chang'a, L. B., Liwenga, E. T., Kanemba, A., and Nindi, S. J. (2013). The use of indigenous knowledge in weather and climate prediction in Mahenge and Ismani wards. *Journal of Geography and Regional Planning,* 6 (7).

Kohtala, C. (2014). Addressing sustainability in research on distributed production: an integrated literature review. *Journal of Cleaner Production.*

Kreiger, M. A., Mulder, M. L., Glover, A. G., and Pearce, J. M. (2014). Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. *Journal of Cleaner Production*, 70, 90-96.

Kreiger, M., and Pearce, J. M. (2013). Environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products. *ACS Sustainable Chemistry and Engineering*, 1(12), 1511-1519.

Lai, A. W. (1995). Consumer values, product benefits and customer value: a consumption behavior approach. *Advances in Consumer Research*, 22, 381.

Lanzotti, A., Martorelli, M., and Staiano, G. (2015). Understanding Process Parameter Effects of RepRap Open-Source Three-Dimensional Printers through a Design of Experiments Approach. *Journal of Manufacturing Science and Engineering,* 137(1).

Lee, J., and Huang, A. (2013). Fatigue analysis of FDM materials. *Rapid Prototyping Journal*, 19(4), 291-299.

Li, L., Sun, Q., Bellehumeur, C., and Gu, P. (2002). Composite modeling and analysis for fabrication of FDM prototypes with locally controlled properties. *Journal of Manufacturing Processes*, 4(2), 129-141.

Ljungberg, L. Y. (2007). Materials selection and design for development of sustainable products. *Materials and Design*, 28(2), 466-479.

Lu, L., Sharf, A., Zhao, H., Wei, Y., Fan, Q., Chen, X., and Chen, B. (2014). Build-to-last: Strength to weight 3D printed objects. *ACM Transactions on Graphics (TOG)*, 33(4), 97.

Mahemba, C. M., and Bruijn, E. J. D. (2003). Innovation Activities by Small and Medium-sized Manufacturing Enterprises in Tanzania. *Creativity and Innovation Management*, 12(3), 162-173.

Melles, G., de Vere, I., and Misic, V. (2011). Socially responsible design: thinking beyond the triple bottom line to socially responsive and sustainable product design. *CoDesign*, 7(3-4), 143-154.

Melles, G., Kuys, B., Kapoor, A., Rajanayagam, J., Thomas, J., and Mahalingam, A. (2015). Designing Technology, Services and Systems for Social Impact in the Developing World: Strong Sustainability Required. *Proceedings from ICoRD'15– Research into Design Across Boundaries*. Springer India.

Mellor, S., Hao, L., and Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, 149, 194-201.

Mireles, J., Adame, A., Espalin, D., Medina, F., Winker, R., Hoppe, T., and Wicker, R. (2011). Analysis of sealing methods for FDM-fabricated parts. *Proceedings from 22nd International Symposium on Solid Freeform Fabrication.* El Paso, TX: University Of TEXAS-El PASO.

MIT- Material Systems Laboratory. Injection Molding Technical Cost Model. Retrieved from ardent.mit.edu/real_options/Real.../injection_molding_cost_model.xls. Accessed 3/15/2015.

Nancharaiah, T., Raju, D. R., and Raju, V. R. (2010). An experimental investigation on surface quality and dimensional accuracy of FDM components. *International Journal on Emerging Technologies*, 1(2), 106-111.

National Bureau of Statistics. (2013). *Key Findings 2011/2012 Household Budget Survey Tanzania Mainland*. Dar Es Salaam, Tanzania.

Nyman, H. J., and Sarlin, P. (2014, January). From Bits to Atoms: 3D Printing in the Context of Supply Chain Strategies. *Proceedings from System Sciences (HICSS), 2014 47th Hawaii International Conference*. Hawaii.

Okot-Okumu, J. (2012). *Solid Waste Management in African Cities-East Africa*. INTECH Open Access Publisher.

Pearce, J. M., Blair, C. M., Laciak, K. J., Andrews, R., Nosrat, A., and Zelenika-Zovko, I. (2010). 3-D printing of open source appropriate technologies for self-directed sustainable development. *Journal of Sustainable Development*, 3(4), 17.

Percoco, G., Lavecchia, F., and Galantucci, L. (2012). Compressive properties of FDM Rapid Prototypes Treated with a Low Cost Chemical Finishing. *Research Journal of Applied Sciences, Engineering, and Technology*. 4(19), 3838-3842.

Petrovic, V., Vicente Haro Gonzalez, J., Jorda Ferrando, O., Delgado Gordillo, J., Ramon Blasco Puchades, J., and Portoles Grinan, L. (2011). Additive layered manufacturing: sectors of industrial application shown through case studies.International. *Journal of Production Research*, 49(4), 1061-1079.

Pîrjan, A., and Petroşanu, D. M. (2013). The Impact of 3D Printing Technology on the Society and Economy. *Journal of Information Systems and Operations Management*, 7(2), 360-370.

Polak, P. (2010). Why Ending Poverty is Greener than Green. http://www.paulpolak.com/why-ending-poverty-is-greener-than-green/

Polak, P. (2008). *Out of Poverty: What Works When Traditional Approaches Fail*. San Francisco, Calif.: Berrett-Koehler.

Porter, M.E. (1980). *Competitive Strategy*. The Free press, New York.

Rao, A.S., Dharap, M.A., Venkatesh, J.V.L., and Ojha, D. (2012) Investigation of Post Processing Techniques to Reduce the Surface Roughness of Fused Deposition Modeled Parts. *International. Journal of Mechanical Engineering and Technology*, 3 (3).

Raut, S., Jatti, V. S., Khedkar, N. K., and Singh, T. P. (2014). Investigation of the Effect of Built Orientation on Mechanical Properties and Total Cost of FDM Parts. *Procedia Materials Science,* 6, 1625-1630.

RubeGolberg. (2013). Calipers 2.0 -Metric. Retrieved from http://www.thingiverse.com/thing:47955

Rutkowski, J. V., and Levin, B. C. (1986). Acrylonitrile–butadiene–styrene copolymers (ABS): Pyrolysis and combustion products and their toxicity—a review of the literature. *Fire and materials*, 10(3-4), 93-105.

Sanders, E. B. N., and Stappers, P. J. (2008). Co-creation and the new landscapes of design. *Co-design*, 4(1), 5-18.

Sesan, T., Raman, S., Clifford, M., and Forbes, I. (2013). Corporate-led sustainable development and energy poverty alleviation at the bottom of the pyramid: the case of the cleancook in Nigeria. *World Development*, 45, 137-146.

Sood, A. K., Equbal, A., Toppo, V., Ohdar, R. K., and Mahapatra, S. S. (2012). An investigation on sliding wear of FDM built parts. *CIRP Journal of Manufacturing Science and Technology*, 5(1), 48-54.

Sood, A. K., Ohdar, R. K., and Mahapatra, S. S. (2010). Parametric appraisal of mechanical property of fused deposition modelling processed parts. *Materials and Design*, 31(1), 287-295.

Sood, A. K., Ohdar, R. K., and Mahapatra, S. S. (2012). Experimental investigation and empirical modelling of FDM process for compressive strength improvement. *Journal of Advanced Research*, 3(1), 81-90.

Stava, O., Vanek, J., Benes, B., Carr, N., and Měch, R. (2012). Stress relief: improving structural strength of 3D printable objects. *ACM Transactions on Graphics (TOG)*, 31(4), 48.

Stephens, B., Azimi, P., El Orch, Z., and Ramos, T. (2013). Ultrafine particle emissions from desktop 3D printers. *Atmospheric Environment*, 79, 334-339.

Sustainable Development Knowledge Platform. (2015). *Open Working Group proposal for Sustainable Development Goals.* United Nations Department of Economic and Social Affairs. Retrieved from https://sustainabledevelopment.un.org/sdgsproposal. Accessed 3/3/2015.

TANESCO. (2015). Electricity Charges: Domestic Low Use Charges. http://www.tanesco.co.tz/index.php?option=com_content&view=article&id=63&Itemid=205. Accessed 3/20/2015.

TANESCO. (2015). Hydro Power Plants. http://www.tanesco.co.tz/index.php?option=com_content&view=article&id=77&Itemid=16. Accessed 4/5/2015.

Tatham, P., Loy, J., and Peretti, U. (2014). 3D Printing (3DP): A humanitarian logistic game changer? Griffith University. Retrieved from: http://www98.griffith.edu.au/dspace/bitstream/handle/10072/62689/96233_1.pdf?sequence=1. Accessed 1/25/2015.

Thoppil, Dhanya Ann. (2014). "Unlikely Startup Connects India's Garbage Dumps to 3-D Design". *The Wall Street Journal*. Retrieved from http://blogs.wsj.com/indiarealtime/2014/10/07/unlikely-startup-connects-indias-dumps-to-3d-design/. Accessed 3/28/2015.

Tierney, John. (2014). "The Company That Turns Plastic Bottles into Fabric-and Jobs." *The Atlantic*. Retrieved from http://www.theatlantic.com/business/archive/2014/11/the-company-that-turns-plastic-bottles-into-fabricand-jobs/382473/. Accessed 2/25/2015.

Tymrak, B. M., Kreiger, M., and Pearce, J. M. (2014). Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. *Materials and Design*, 58, 242-246.

Uiterkamp, B. J. S., Azadi, H., and Ho, P. (2011). Sustainable recycling model: A comparative analysis between India and Tanzania. *Resources, Conservation and Recycling*, 55(3), 344-355.

United Nations Economic Commission for Africa. (2012). Africa Review Report on Waste Management: Executive Summary. Retrieved from http://www.uncsd2012.org/content/documents/AfricanReviewReport-onWasteManagementSummary.pdf. Accessed 2/5/2015.

United Nations Environment Programme. (2009). *Design for Sustainability: A Step-By-Step Approach*. Paris, France: United Nations Environment Program.

Valentan, B., Brajlih, T., Drstvensek, I., and Balic, J. (2008). Basic solutions on shape complexity evaluation of STL data. *Journal of Achievements in Materials and Manufacturing Engineering*, 26(1), 73-80.

Valentan, B., Brajlih, T., Drstvenšek, I., and Balič, J. (2012). Development of a part-complexity evaluation model for application in additive fabrication technologies. *Strojniški vestnik-Journal of Mechanical Engineering*, 57(10), 709-718.

Walls, S., Corney, J., and Vasantha, G. (2014). Relative Energy Consumption of Low-Cost 3D printer. *Proceedings of the 12th International Conference on*

Manufacturing Research (ICMR2014). Glasgow, Scotland: University of Strathclyde.

Weiss, L. (2002). Developing tangible strategies. *Design Management Journal (Former Series)*, 13(1), 33-38.

White, C., Stewart, E., Howes, T., and Adams, B. (2008). *Aligned for Sustainable Design: An ABCD Approach to Making Better Products*. BSR, IDEO.

Whitehead, Timothy, Mark Evans, and Guy Bingham. (2014). A Framework for Design and Assessment of Products in Developing Countries. Loughborough University. Retrieved from: http://www.drs2014.org/media/654441/0313-file1.pdf

Wittbrodt, B. T., Glover, A. G., Laureto, J., Anzalone, G. C., Oppliger, D., Irwin, J. L., and Pearce, J. M. (2013). Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. *Mechatronics*, 23(6), 713-726.

Yeh, C. C. (2014). Trend Analysis for the Market and Application Development of 3D Printing. *International Journal of Automation and Smart Technology*, 4(1), 1-3.

Yoon, H. S., Lee, J. Y., Kim, H. S., Kim, M. S., Kim, E. S., Shin, Y. J., and Ahn, S. H. (2014). A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 1(3), 261-279.

Appendix A. Methodology for the Calculation of the Volume of Filament Needed to Print an Object

Calcuations and Methodology

In Section 3.2 a series of equations were utilized to calulcate the cost of producing a part using 3D printing. This process started by using an Equation 3 from Mello (Mello et al., 2010).

$$C_{part} = C_{pre} + E_{total} * C_{energy} + m_{filament} * C_{filament} + C_{post} \qquad \text{Equation 3}$$

As nearly all of the costs associated with 3D printing are in the build phase, this equation is simplified into Equation 3a.

$$C_{part} = E_{total} * C_{energy} + m_{filament} * C_{filament} \qquad \text{Equation 3a}$$

The mass of the filament, m_f, is related to the size of the part, as is the amount of energy used, E_{total} (Wittbrodt et al., 2013). Build parameters, such as layer height, flowrate, infill, and deposition speed, will ultimately affect the final cost of a part. It was shown in Figure 13 that by knowing the volume of filament used, cost estimations can be greatly simplified using Equation 5 below.

$$C_{part} \approx V_{filament} * \rho_{filament} * C_{filament} \text{ (USD)} \qquad \text{Equation 5}$$

where $V_f = \text{the filament used to produce the part}$ (mm^3)

Thus it becomes necessary to predict the volume of filament used. This is a challenge, however, as the amount of filament needed can vary greatly based on porosity and infill changes. In order to develop methodology for calculating this volume, data from a series of experiments published in works by both Kreiger (Kreiger et al., 2014) and Wittbrodt (Wittbrodt et al., 2013) was used. This data included 20 items available for download from the open source website “Thingiverse”. These 20 assorted products were printed using a RepRap Prusa Mendel. Many variables were tracked throughout the print process including time of build, energy used, and the mass of filament used. Different parts used different build parameters, and some of these build parameters were also recorded. The volume of each part is attained by downloading open source STL files from the website Thingiverse. By comparing the volumes in Figure 20, it can be seen that the volume of filament used is always less than the geometric volume of the part, however, this is to be expected. As discussed in Section 3.2, the volume of a part deviates from its actual volume because of porosity and reduced infill. While calculations for porosity can be made separately from calculations of infill, these methodologies will treat them as one calculation because infill reductions account for most of the difference in volume.

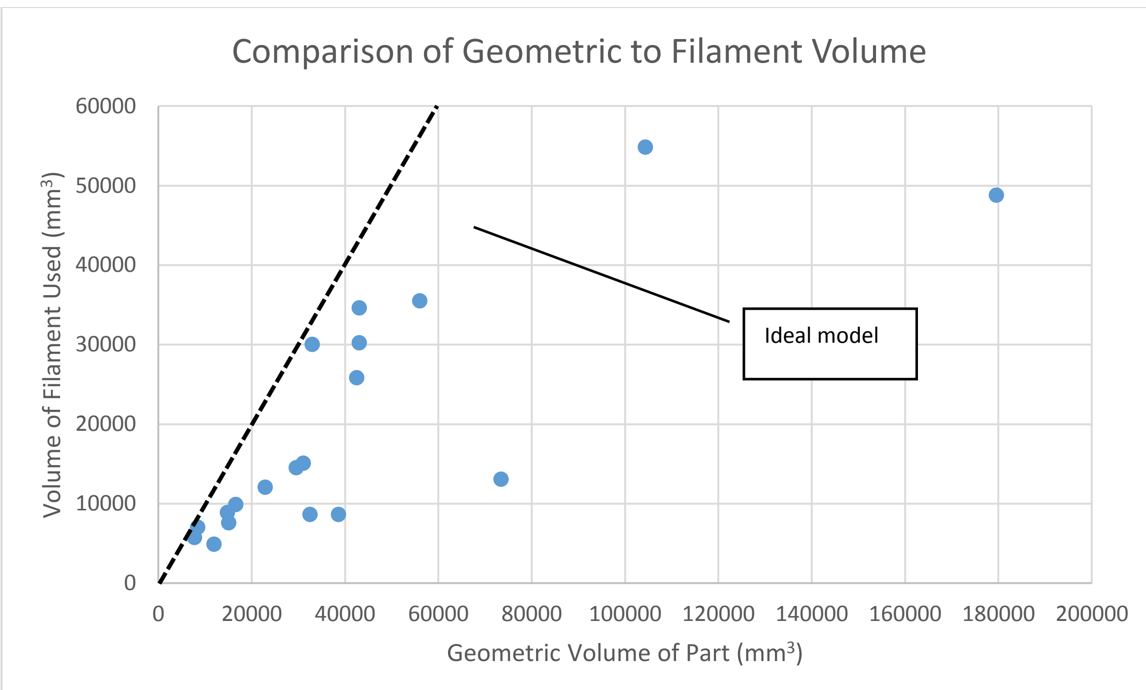


Figure 20. Volume of filament needed vs geometric volume of a part (adapted from Wittbrodt et al. 2013)

Method 1: Filament Volume Predictions Based Upon Product of Geometric Volume and Infill Percentage

The simplest approach is to predict the volume of the part by the percentage infill. This is given by Equation 10 below

$$V_{filament} = V_{part} * I \qquad \text{Equation 10}$$

where I = fraction infill prescribed

This model was fit to the data from Wittbrodt (Wittbrodt et al. 2013) as seen in Figure 21 below. While the infill fraction model is much better able to predict the volume of filament needed than using the geometric volume alone, it significantly deviates from the actual filament needed for parts with low volumes.

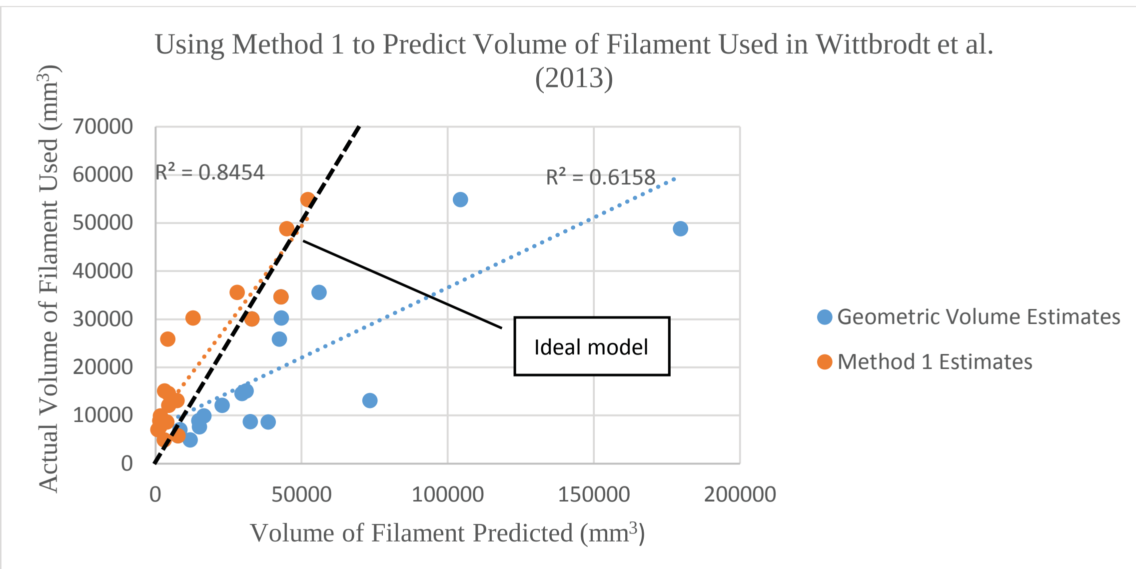


Figure 21. Comparison of geometric volume and the product of geometric volume and infill to predict filament volume

In order to make more accurate models, more data points are necessary. While ideally this could be accomplished by printing and taking experimental measurements on a variety of parts, this was not in the scope of this study. However, the volume of filament used to print a part can be calculated with a high degree of accuracy by using slicing software. Wittbrodt used the open source software Cura to calculate the mass of the filament needed to produce parts given specific build parameters (Wittbrodt et al., 2013). Though the estimates that Cura provided were erroneous, this error could largely be attributed to density constants that did not reflect the actual properties of the filament (Wittbrodt et al., 2013). With small corrections accounting for these discrepancies, the Cura estimates prove to be able to accurate.

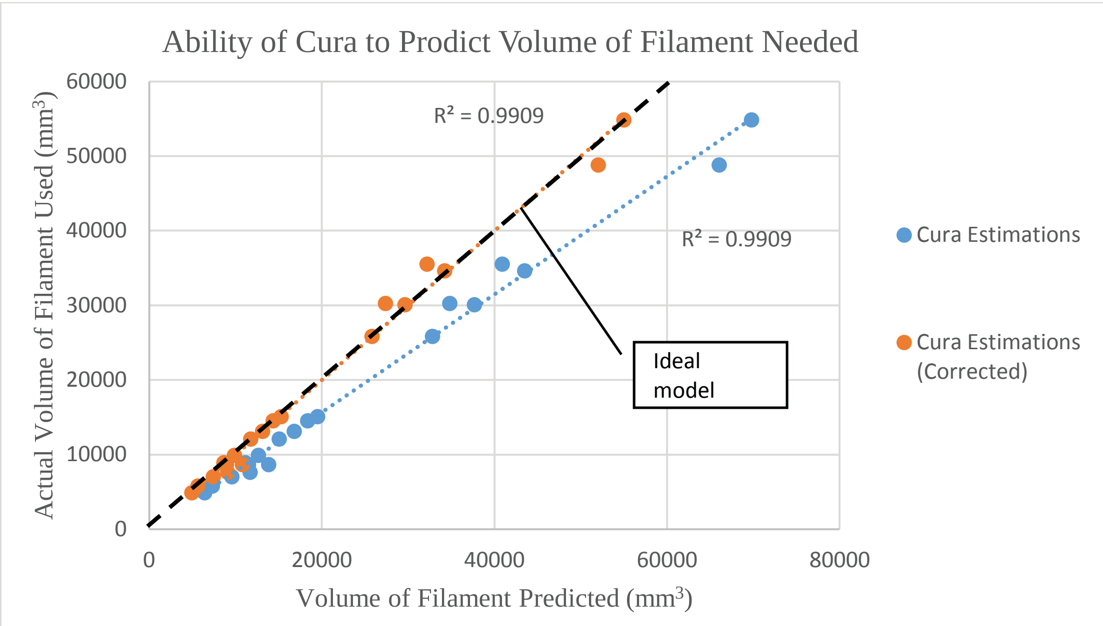


Figure 22. Cura estimated volumes in comparison to experimental measurements (data adapted from Wittbrodt et al., 2013)

Thus, if necessary to determine the volume of filament needed for a print, slicing software is the most accurate way to make predictions. Slicing software does require, however, a completed STL file to make estimates. If beginning a preliminary assessment of producing a part with 3D printing, or if a STL file or computer with slicing software are not available it becomes necessary to find additional methodology for calculating the amount of filament needed.

Because it was not possible to measure experimental values, the following methodologies were not based on experimental data, but rather simulated data from Cura software. As demonstrated in Figure 22, Cura data is able to be consistently related to experimental data and these methods could be recalibrated as experimental data becomes available. The simulation of these prints was undertaken by downloading 60 STL files from the open source website “Thingiverse”. All of these objects were a variety of shapes and sizes that met the following conditions:

1. The print could fit within a build envelope of 200mm by 200mm by 200mm. A size that is comparable to most low cost 3D printers.

2. The print was comprised of a single part.

3. The print, by the author’s observation, would require minimal scaffolding and support filament to produce.

Cura was then used to estimate the mass of filament needed for printing each of the 60 parts using infills of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. Thus 600 simulated data points were created. While other factors such as layer height can also influence the volume of filament used, the geometric volume of the part and infill percentage are the most significant variables. The amount of infill that can be removed from a part varies dramatically by geometry.

Method 2: Filament Volume Predictions Based upon Surface Area and Shell Thickness

The second method to estimate the volume of filament needed is based upon surface area of a part. As the shell, or outermost layer of a product, cannot have its volume reduced without visible external consequences, this mass of the part cannot change and thus the volume associated with it does not change with infill conditions. This is shown in Figure 23 below.

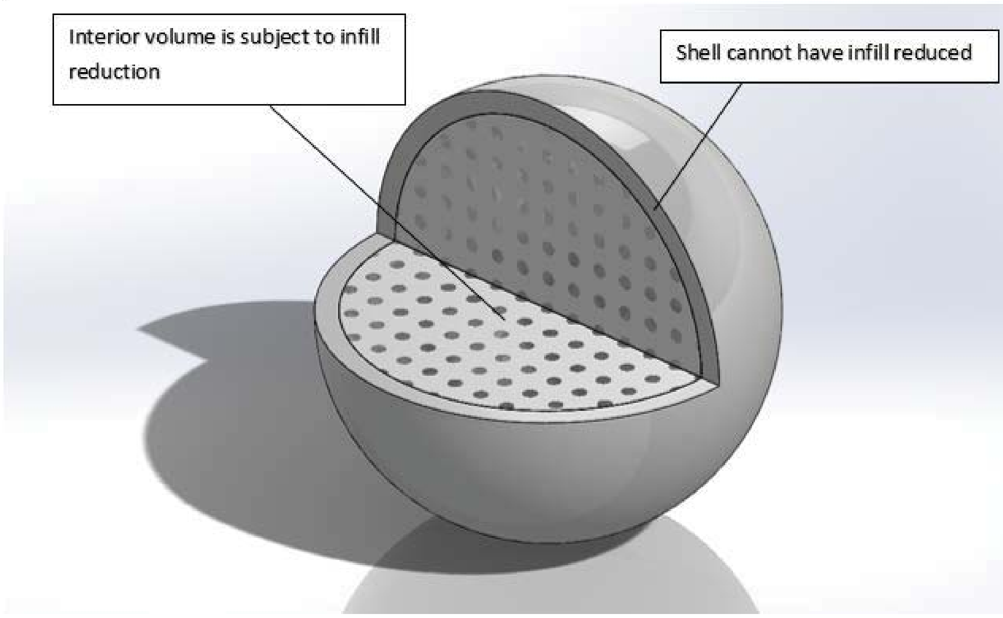


Figure 23. Thickness volume and interior volume of a 3D printed part (rendered by author using Solidworks)

Thus, in order to calculate the total volume of filament needed, Method 2 views the printed object as two different parts: the shell and the interior volume. The volume of the shell was estimated with the Equation 11 below:

$$V_{\text{shell}} = A_{\text{surface}} * \text{th} * \text{c} \qquad \text{Equation 11}$$

where V_{shell} = volume associated with the surface area (mm^3)

A_{surface} = surface area of a part (mm^2)

th = thickness of shell (mm)

c = correction factor

By examining the data from the 600 simulated prints through Cura, a bias correction factor of 1.06 was subsequently incorporated to allow the model to better to match the data. The volume of the shell will not actually be equal to the surface area times the shell thickness and will be dependent on the geometry of the printed part.

Equation 9 only accounts for the shell volume, and of course the interior volume must also be accounted for. The interior volume is equal to the part's total geometric volume less the volume used by the shell. However, the interior is only partially filled by an amount determined by the infill percentage. This can be accounted for with Equation 12 below.

$$V_{interior} = \left(V_{part} - V_{shell}\right) * I \qquad \text{Equation 12}$$

where $V_{interior}$ = the interior volume of the part (mm^3)

The total volume of filament can then be calculated by using Equation 13, and expanded in Equation 14.

$$V_{filament} = V_{interior} + V_{shell} \qquad \text{Equation 13}$$

$$V_{filament} = \left[V_{part} - (A_{surface} * th * c)\right] * I + A_{surface} * th * c \qquad \text{Equation 14}$$

This surface area based model was shown to match the simulated data points well as seen in Figure 24 below.

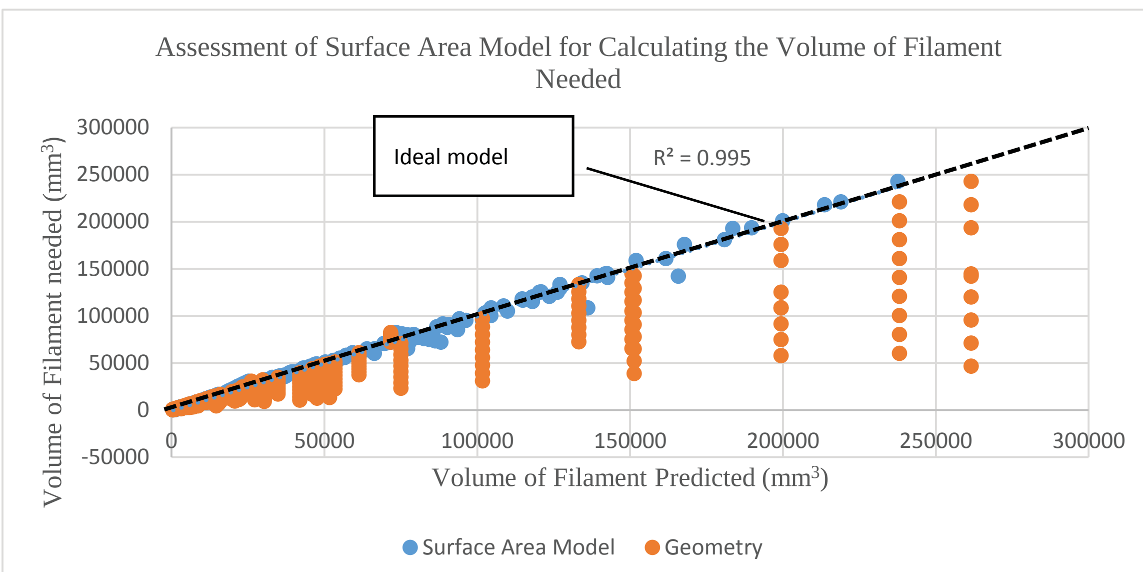


Figure 24. Comparison of Method 2 (Surface Area Model) to predictions made on geometry alone

Method 2 (Surface Area Model) was subsequently compared to the measured experimental data points available from Wittbrodt et al. (2013), correcting for the differences in Cura. The results can be seen in Figure 25.

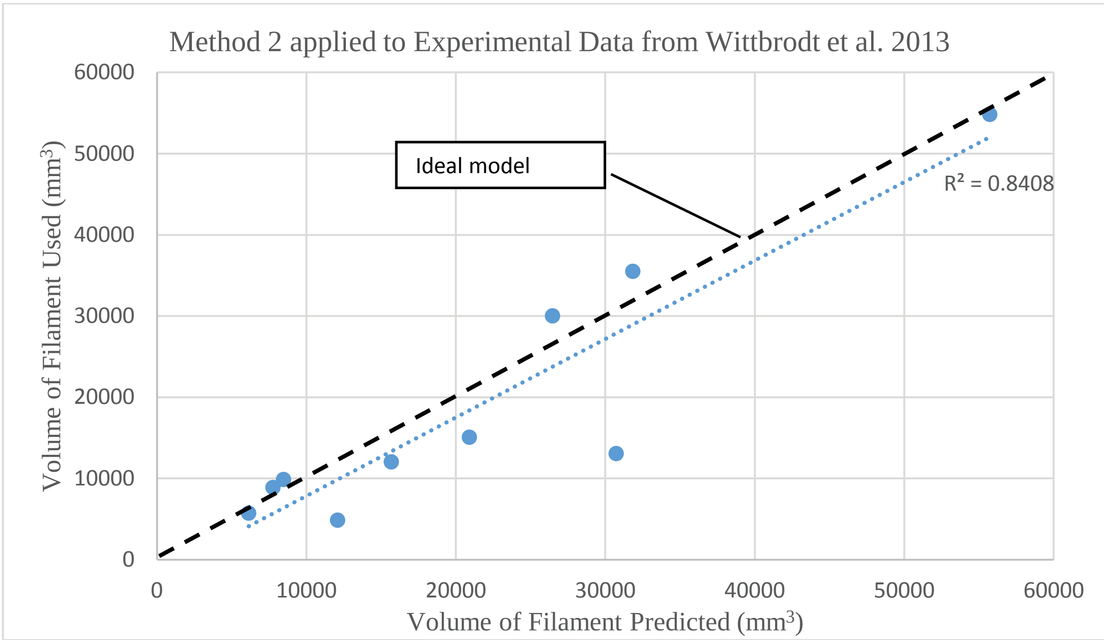


Figure 25. Application of Method 2 (surface area model) to Data (adapted from Wittbrodt et al. 2013)

However, this surface area model's ability to predict volume used is limited for quick calculations. The surface area of a part can be difficult to calculate for some parts based on only manual measurements, and it became necessary to develop additional techniques. Thus an additional modeling method was employed.

Method 3: Filament Volume Predictions Based upon Slice Perimeter and Area

This technique considers the printed part not as a volume, but as a series of slices. As discussed in the surface area method, the surface area of the part cannot be taken into account when removing infill, and thus the imperative is to determine the amount of volume that the shell will account for and remove that from the total volume of the part. The volume that remains will be what is subjected to infill removal.

The area of an average slice can be determined by taking the part's geometric volume and dividing it by the height of the object, as seen in Equation 15 below.

$$A_{slice} = \frac{V_{part}}{h} \qquad \text{Equation 15}$$

where $A_s =$ area of a slice of a cylinder withvolume and height of object (mm ^{2})

h = Height of the object (mm)

By using the known geometric volume of the part it can be compared to a cylinder of the same volume and height. A cylinder is a stacking of circular slices and therefore the simplest geometry that exists from the standpoint of an FDM printer. By comparing the ratio of average perimeter of all of an object's slices to the average perimeter of a circular slice from a cylinder of the same volume, the complexity of a 3D printed object can effectively be quantified. An example of this can be seen in Equation 16 below.

$$U = \frac{\frac{1}{N}\sum_{i=1}^{N} P_i}{P_{min}} \qquad \text{Equation 16}$$

where U = Average complexity of an object's slices

P = Average perimeter of the slices (mm)

P_{min} = Perimeter of a slice from a cylinder of the same volume as the object (mm)

N = Number of slices

The minimum perimeter of a slice is equal to the perimeter of a circle with the same area as the slice, and it can be calculated using Equation 17.

$$P_{min} = 2\sqrt{\pi A_{slice}} \qquad \text{Equation 17}$$

The more that an object's slices resembled circular areas, the closer the complexity of that object (U) would be to 1. This is illustrated in Figure 26 below.

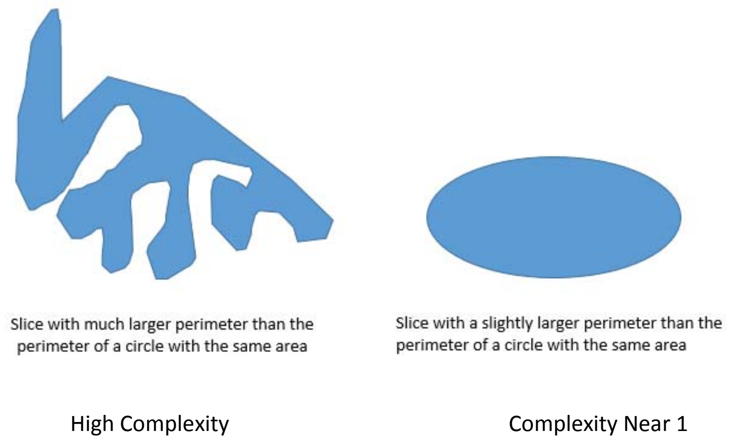
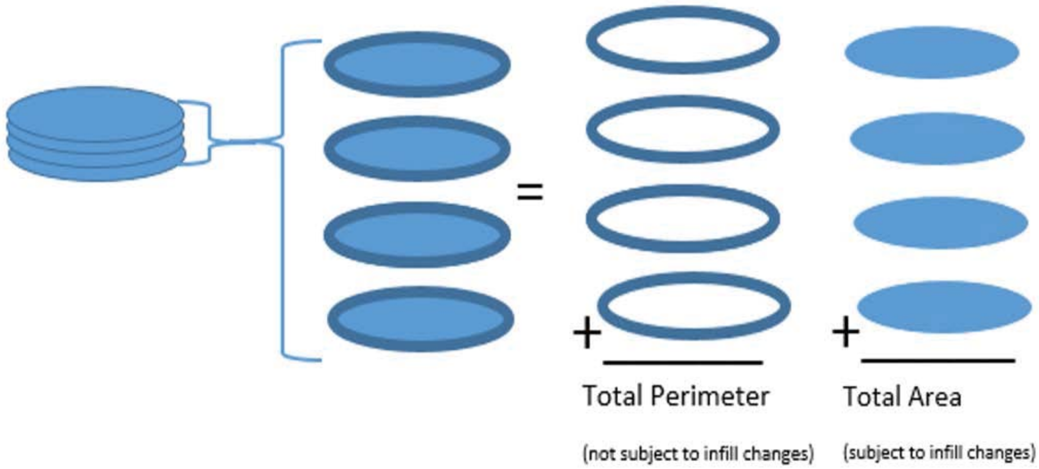


Figure 26. Examples of how slice geometry affects complexity, U

Thus, the total volume of filament used can be approximated by relating the area of an average slice to the average perimeter and multiplying them by the total height as seen in Equation 18 below.

$$V_{filament} = h * \ [U * P_{min} * th + (A_{slice} - U * P_{min} * th) * I] \qquad \text{Equation 18}$$

Like Method 2, this relies on calculating both the surface area and interior volume and then combining the values. However, instead of viewing the two parts as volumes, it regards them as total areas and then multiplies the total area by the height of the object. An illustration of how this equation relates to geometry can be seen in Figure 29.



$$V_{filament} = h * \left[U * P_{min} * th + (A_{slice} - U * P_{min} * th) * I\right]$$

Figure 29. Explanation of how surface area and perimeter relate to Equation 18

While complexity could be estimated by the designer when using Equation 18, it is difficult to quantify how much a part deviates from the geometry of a cylinder. Thus, by examining the 600 simulated data points an equation was developed to predict values for complexity (U) based upon the product of the average slice area (A_s), the minimum perimeter (P_{min}), and the relationship of the volume of an object to the box that contains it, a measure of complexity borrowed from Connor et al. (2012). This relationship is given by Equation 19. The constant parameters were acquired by fitting complexity values, U, that when applied to Equation 18 would yield filament volumes that matched the 600 simulated data points.

$$U = \frac{1.4021\left[A_{slice} * P_{min} * \left(1 - \frac{V_{part}}{l * w * h}\right)\right]^{0.5189}}{P_{min}} \qquad \text{Equation 19}$$

where w = maximum width of the part (mm)

l = maximum width of the part (mm)

The effectiveness of this equation can be seen in Figure 30 below.

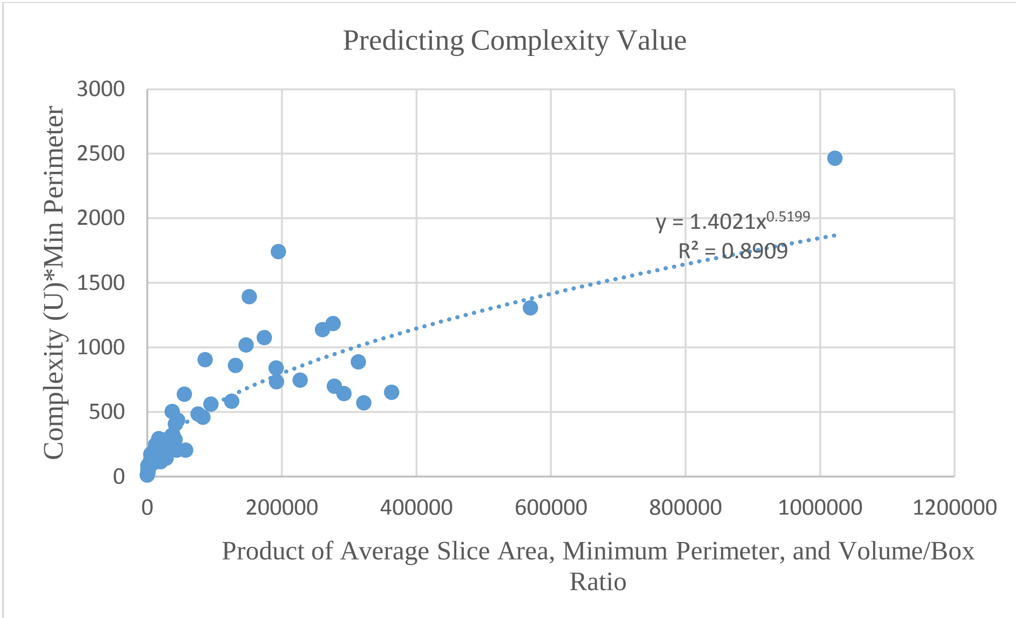


Figure 30. Predicting complexity (U) using Equation 19

It should be noted that this equation fails to reliably predict part complexity as the volume of the part increases. The fit of this predictive curve can be improved significantly if a second measure of complexity, the ratio of surface area to volume of a part, is introduced from Conner et al. (2012). This additional factor is incorporated into Equation 20.

$$U = \frac{0.6933\left[A_{slice} * P_{min} * \left(1 - \frac{V_{part}}{l * w * h}\right) * \frac{A_{surface}}{V_{part}}\right]^{0.623}}{P_{min}} \qquad \text{Equation 20}$$

The results of this model can be used to better predict the complexity of a geometry, even at higher volumes. Results are shown in Figure 31.

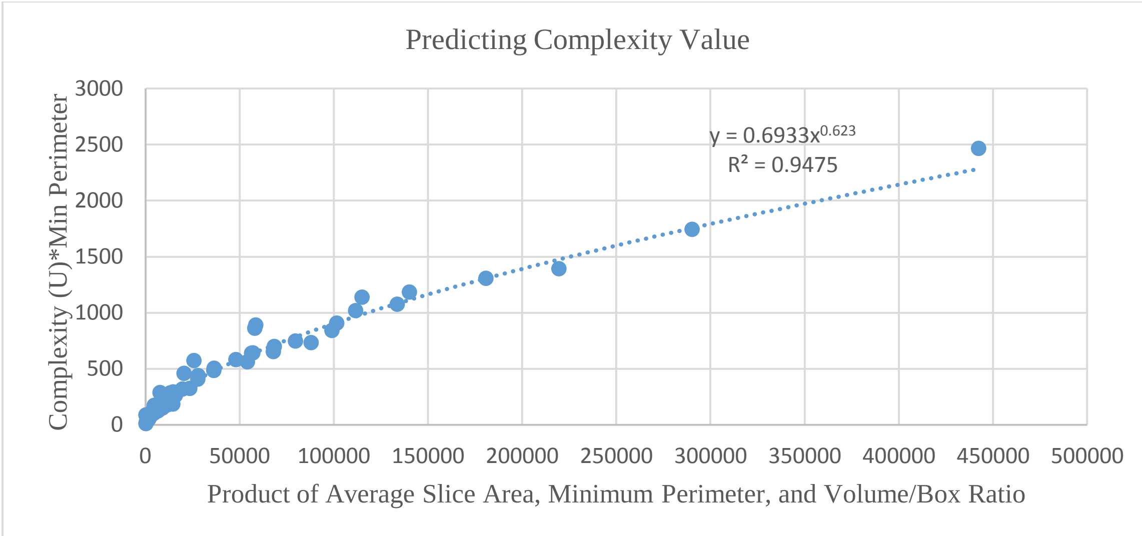


Figure 31. Predicting complexity (U) using Equation 18

However, Equation 18 can only be used if the surface area of the part is known. As this was one of the reasons that Equation 12 was considered insufficient, Equation 17 can still be used if surface area cannot be calculated.

Both Equations 17 and 18, when applied with Equation 16, are able to predict the volume of parts with a relatively consistent degree of accuracy. Equation 18 appears to be more consistent for smaller volumes, while both formulas struggle to accurately predict larger volumes. The results of both models can be seen in Figure 32.

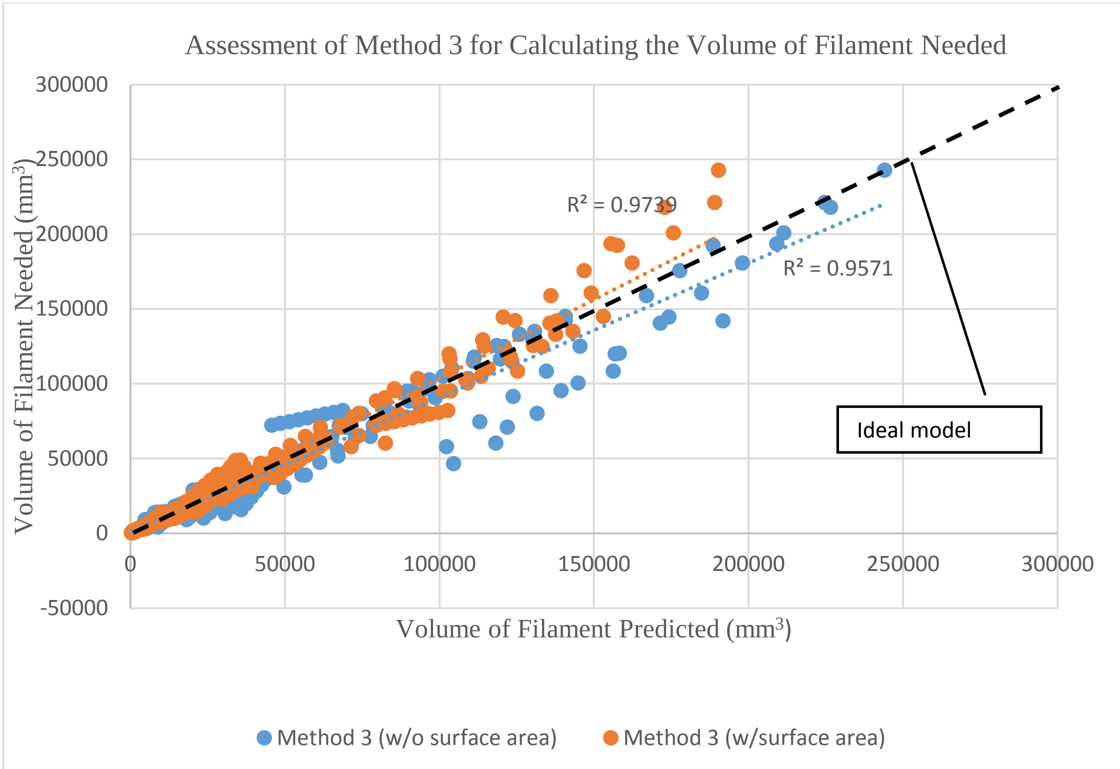


Figure 32. Evaluation of both variations of Method 3 to calculate the volume of filament needed

It can be seen that both of these methods are able to calculate the volume of filament needed to be used. Figure 32 suggests that Method 3 is better when surface area is incorporated. However, when applied to the experimental data from Wittbrodt et al. (2013), it appears from the data is that Method 3 is better when surface area is not incorporated. This is shown in Figure 33.

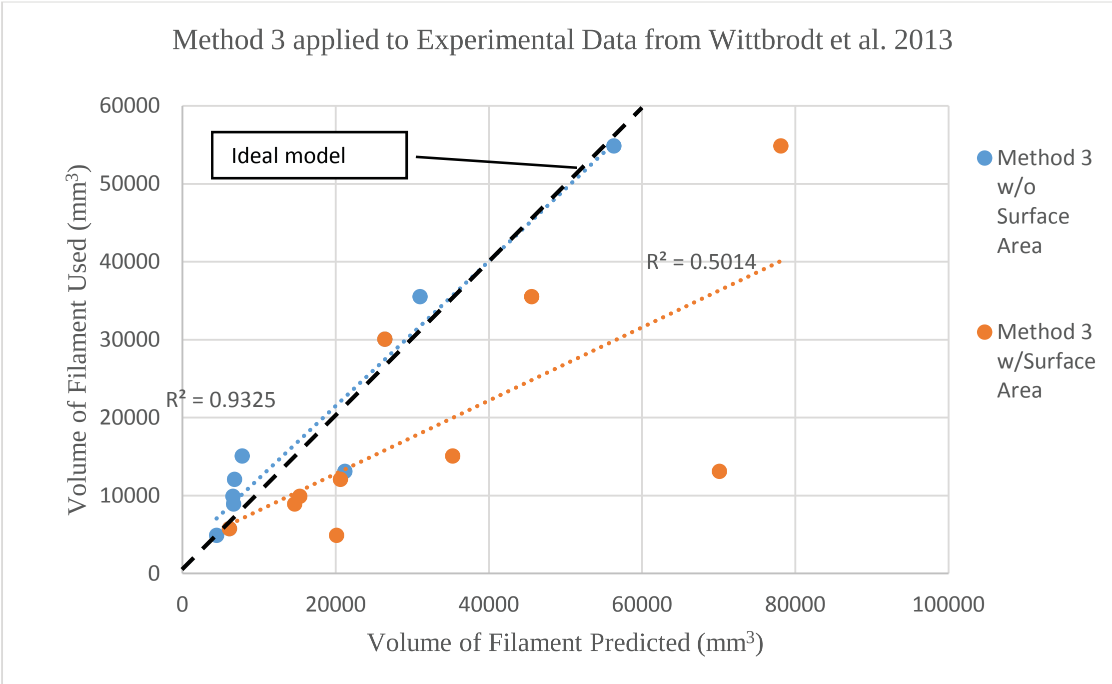


Figure 33. Application of both variations of Method 3 to experimental data (data adapted from Wittbrodt et al., 2013.

Though Method 3 with surface area incorporated appeared to much better match the simulated data, it performed poorly when applied to the limited experimental data from Wittbrodt (Wittbrodt et al., 2013). The reasons for this are unclear and require further investigation. Possible reasons could be errors in calculation or insufficient data points.

Summary of Methods

By examining Equation 1 and the data from Kreiger, it can be seen that determining the mass of the filament is by far the most important factor in calculating the price of 3D printing an object (Kreiger et al., 2014). By determining the volume of filament used, the mass can be easily calculated. Three different methods for determining the volume of filament needed were devised and compared to both experimental and simulated 3D prints. A summary of these methods can be seen in Table 21.

Table 21. Comparison of methodologies for calculating the volume of filament used

Method	**Required Inputs**	**Fit to Simulation Data (R^2)**	**Fit to Experimental Data from Wittbrodt et al. (2013). (R^2)**
Cura	Completed STL file and build parameters	1	0.9961
Geometric Volume	Volume of part	0.8237	0.6750
Method 1	Volume of part and Infill	0.9482	0.9267
Method 2	Volume of part, surface area and infill	0.9950	0.8408
Method 3 (w/o Surface Area)	Volume of part, infill, and maximum length, width, and height	0.9571	0.9325
Method 3 (w/o Surface Area)	Volume of part, infill, surface area, and maximum length, width, and height	0.9739	0.5014

Visual representations of these models can be seen in Figures 34 and 35.

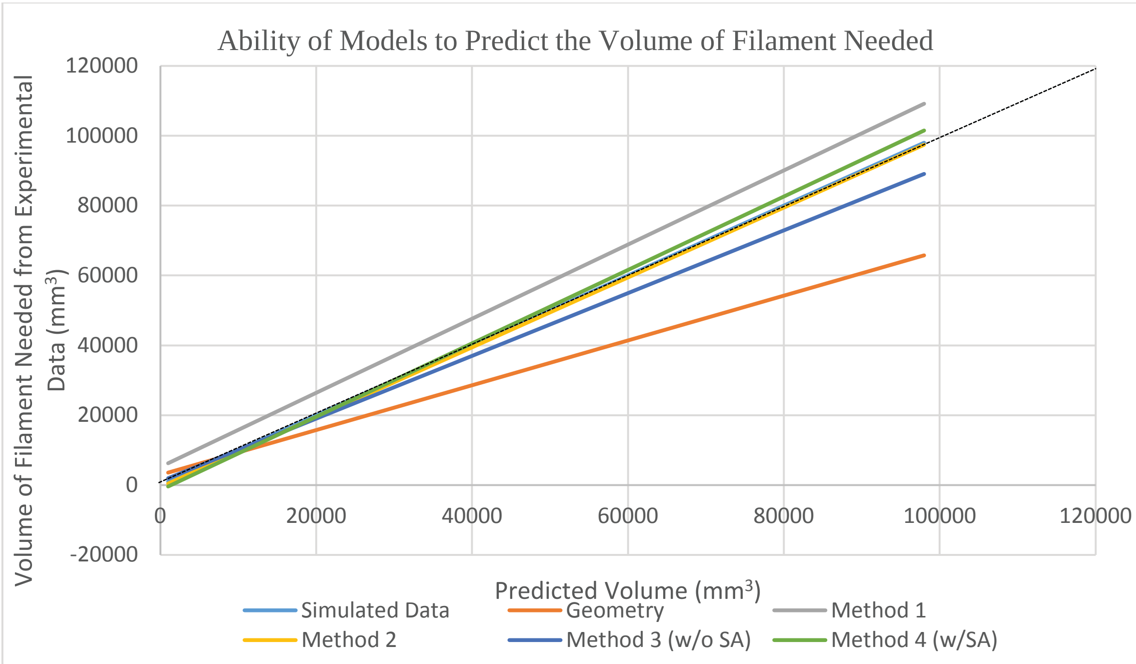


Figure 34. Comparison of models

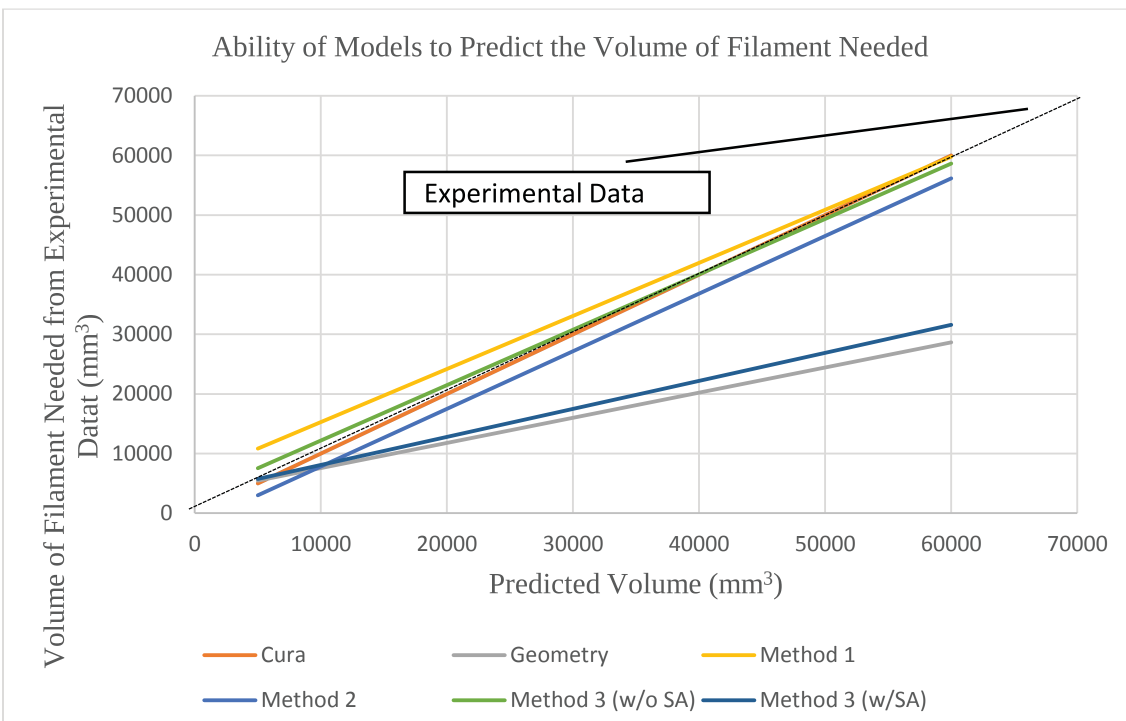


Figure 35. Comparison of models' abilities to match experimental results

(data adapted from Wittbrodt et al. 2013)

The ability to fit to experimental data varied dramatically when the methods were applied to the 600 simulated data points versus the 10 experimental data points taken from Wittbrodt (Wittbrodt et al., 2013). All of the parts manufactured in the study by Wittbrodt were of smaller volumes less than 50,000 mm^3 (Wittbrodt et al., 2013), and the margin of error for all models is typically higher for smaller volume objects. From a cost perspective, this is less concerning as errors in estimates for small volume objects will not result in dramatic differences in filament costs when compared to larger volume objects.

It is evident from Table 20 that the most effective way to predict the volume of filament needed for a print is to use slicing software. However, this requires the most inputs, namely an STL file and build parameters.

In conclusion

Method 1, utilizing geometric volume and infill, is seen to be reasonably effective, and its simplicity is useful for quick calculations, but it is generally a poor fit for smaller volume prints.

Method 2, the Surface Area Model, performed well when compared to the simulated data, but for the relatively few experimental data points, it performed poorly. This could again be due to the general difficulty in accurately predicting very small parts' volume. The other challenge associated with Method 2 is its dependence on knowing the surface area of a part, which may be difficult to calculate for some geometries.

Method 3 (and without surface area taken into account) was the best model for predicting the volume of filament needed in regards to the experimental data. However, Model 3 did not perform as well in regards to fitting the experimental data when surface area was incorporated into the equation. This result was unexpected and will require further investigation to improve.

All methods could be improved by incorporating more of the build parameters beyond infill and shell thickness. Additionally, the role that porosity plays in determining the total volume of filament used should be further explored. Finally, while using simulated data was sufficient for initial calculations, all models could be improved by having more experimental data.